Part I

# FRAGMENTATION MEASUREMENTS @ BELLE

Phenix SpinFest, Urbana, Illinois
July 2014

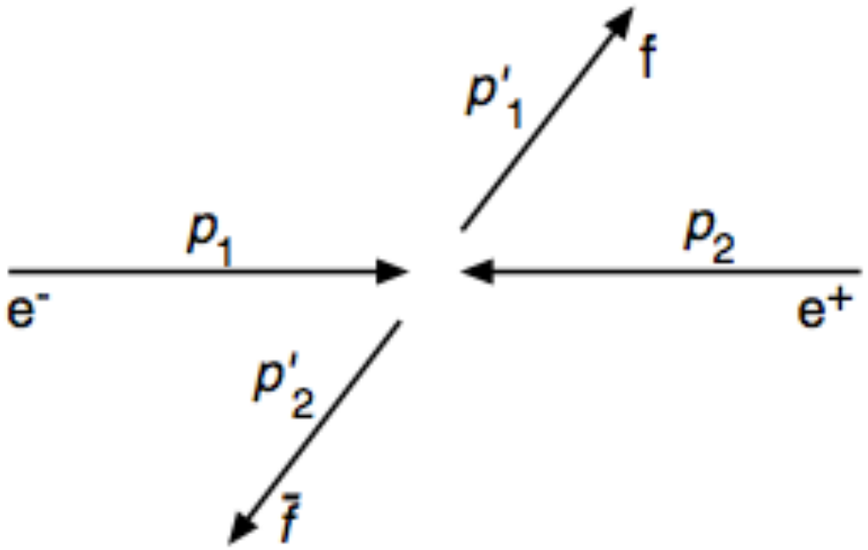
Francesca Giordano

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

BELLE

# $e^+e^-$ annihilation

$$e^+e^- \to f\,\bar{f}$$

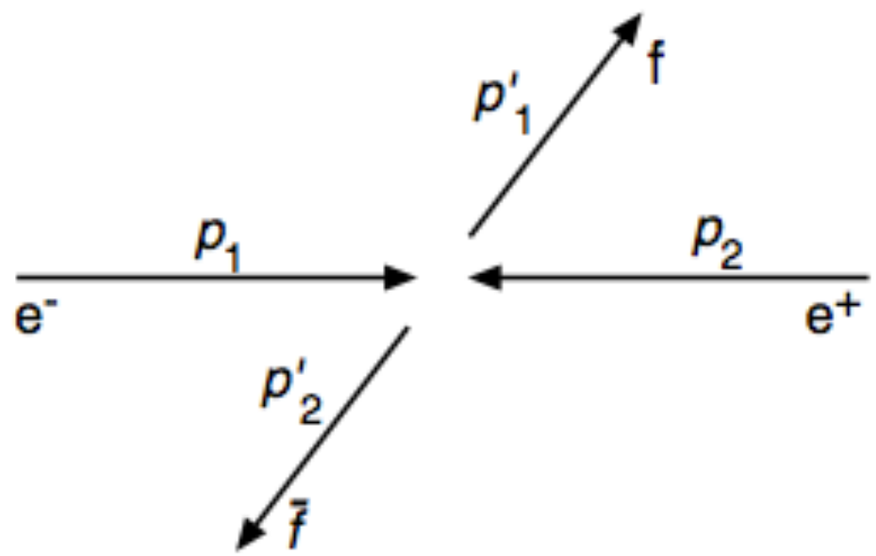



Lorentz-invariant squared center-of-mass-energy:

$$\begin{aligned} s &= (p_1 c + p_2 c)^2 \\ &= m_1^2 c^4 + m_2^2 c^4 + 2E_1 E_2 - 2\boldsymbol{p}_1 \boldsymbol{p}_2 c^2 \end{aligned}$$

# $e^+e^-$ annihilation

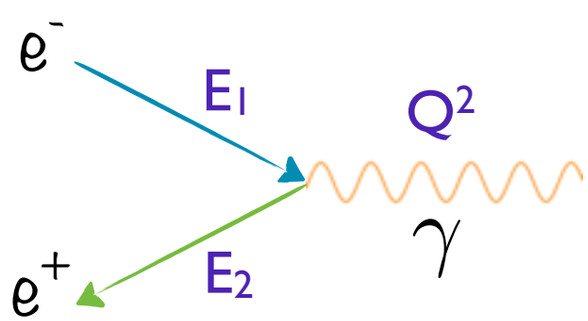
$$e^+e^- \to f\,\bar{f}$$




Lorentz-invariant squared center-of-mass-energy:

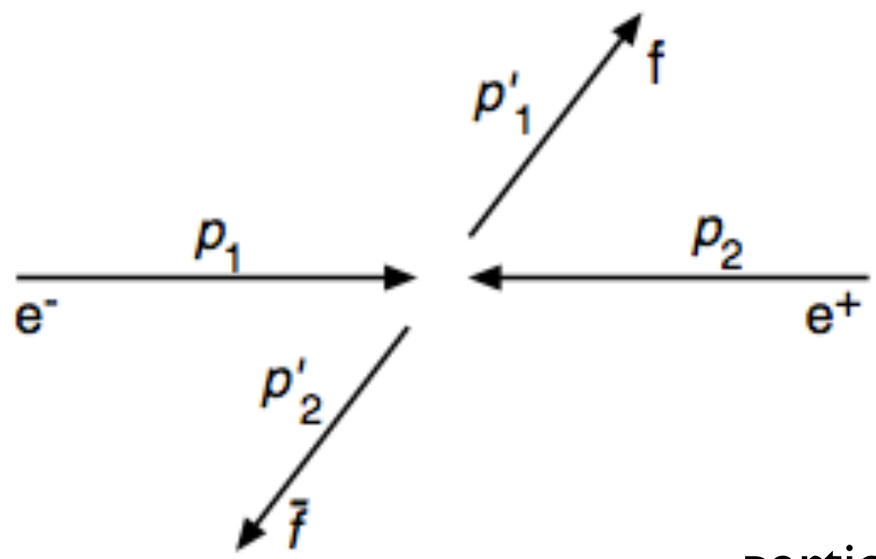
$$s = (p_1 c + p_2 c)^2$$
$$= m_1^2 c^4 + m_2^2 c^4 + 2E_1 E_2 - 2\boldsymbol{p}_1 \boldsymbol{p}_2 c^2$$

$$s = Q^2 c^2$$



# $e^+e^-$ annihilation

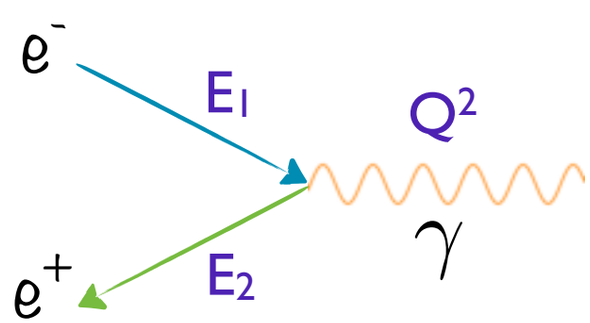
$$e^+e^- \to f\,\bar{f}$$




Lorentz-invariant squared center-of-mass-energy:

$$s = (p_1 c + p_2 c)^2$$
$$= m_1^2 c^4 + m_2^2 c^4 + 2E_1 E_2 - 2\boldsymbol{p}_1 \boldsymbol{p}_2 c^2$$

$$s = Q^2 c^2$$



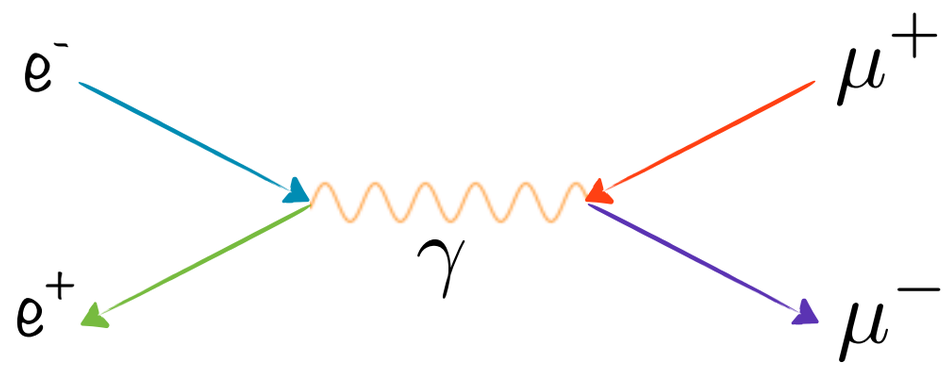

particle/anti-particle mass:

$$m_f \leq \sqrt{s}/2c^2$$

# $e^+e^-$ annihilation

Simplest case
pure QED
($Z_0$ neglected)

$$e^+e^- \to \mu^+\mu^-$$




Cross-section calculable:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2}{4s}(\hbar c)^2 \cdot (1+\cos^2\theta)$$

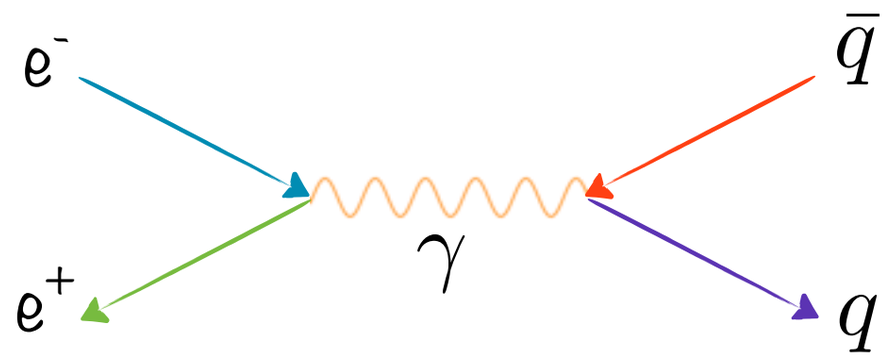
Integrated over $\theta$

$$\sigma = \frac{4\pi\alpha^2}{3s}(\hbar c)^2$$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

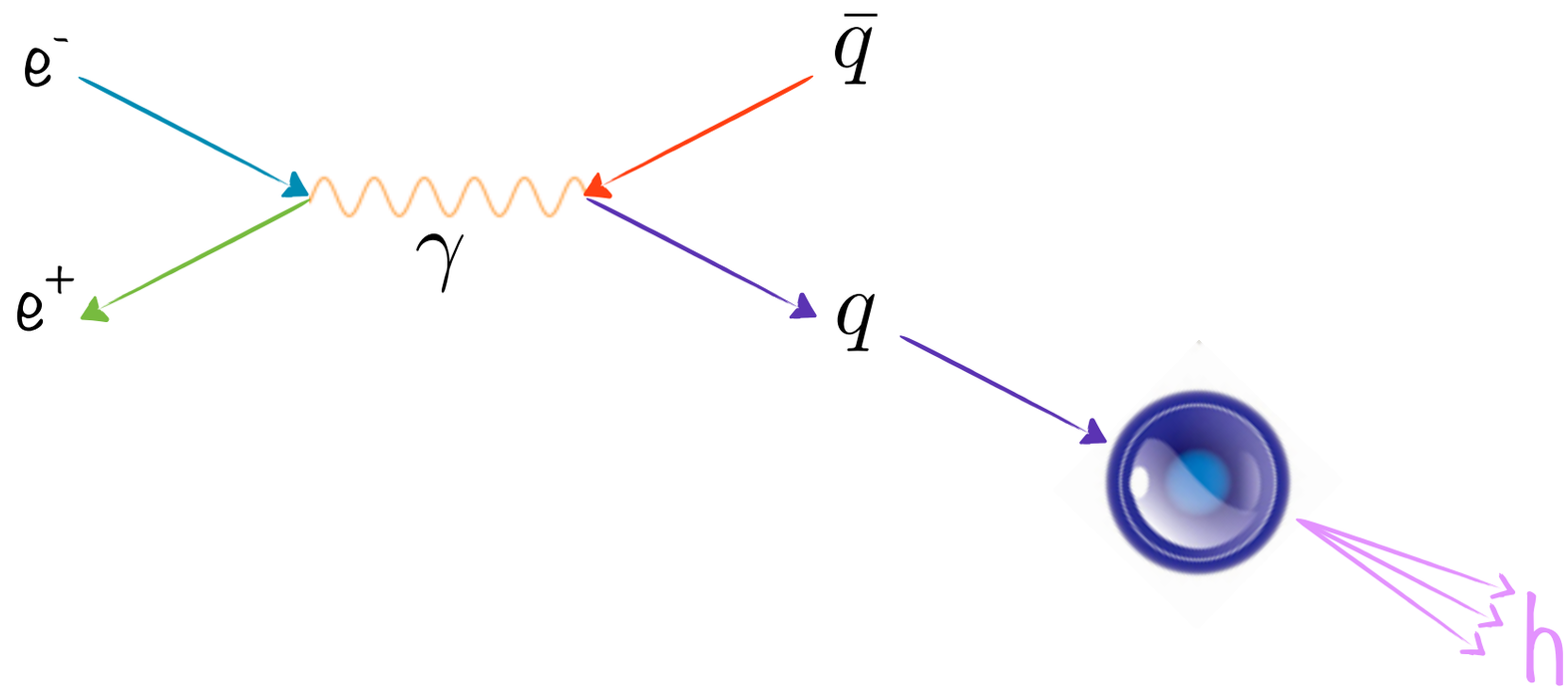
$$e^+e^- \to q\,\bar{q}$$



# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

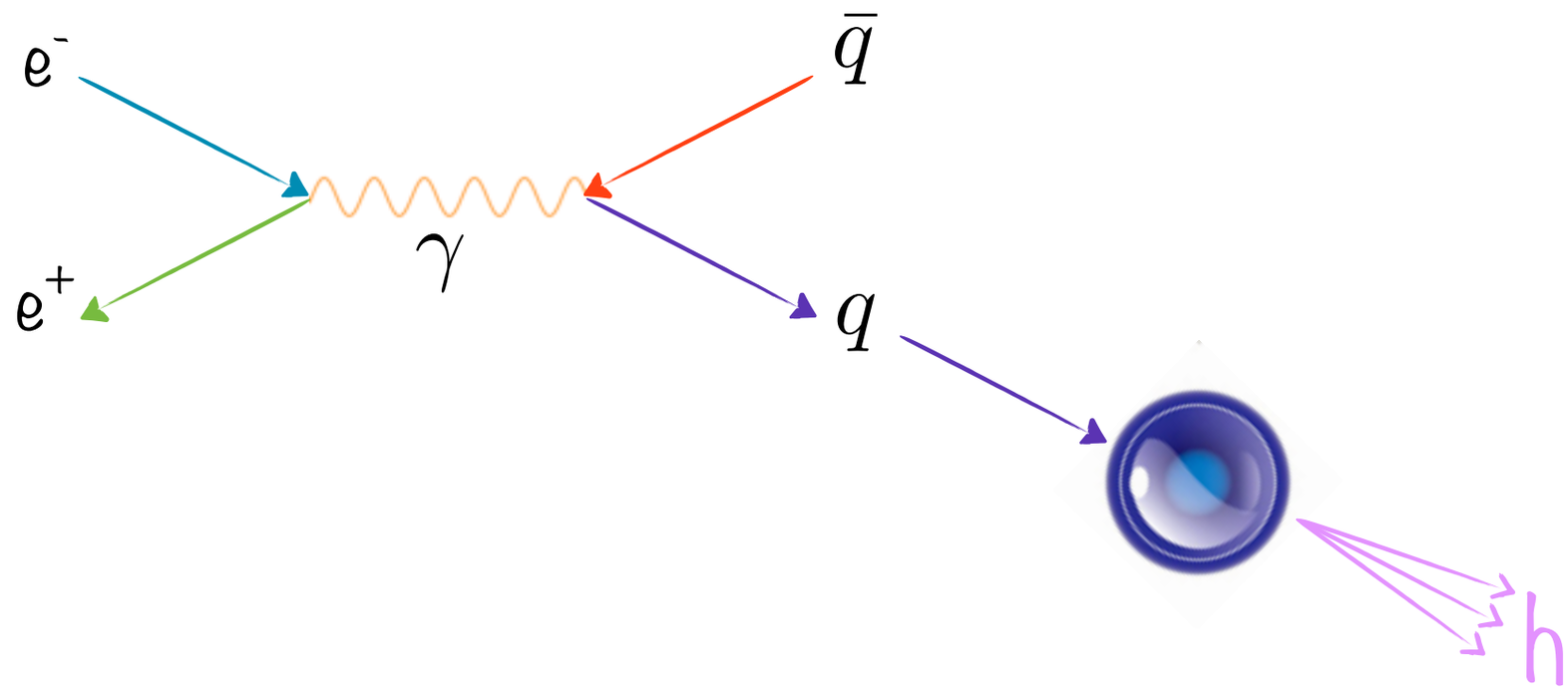
$$e^+e^- \to q\,\bar{q} \to hX$$



# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$

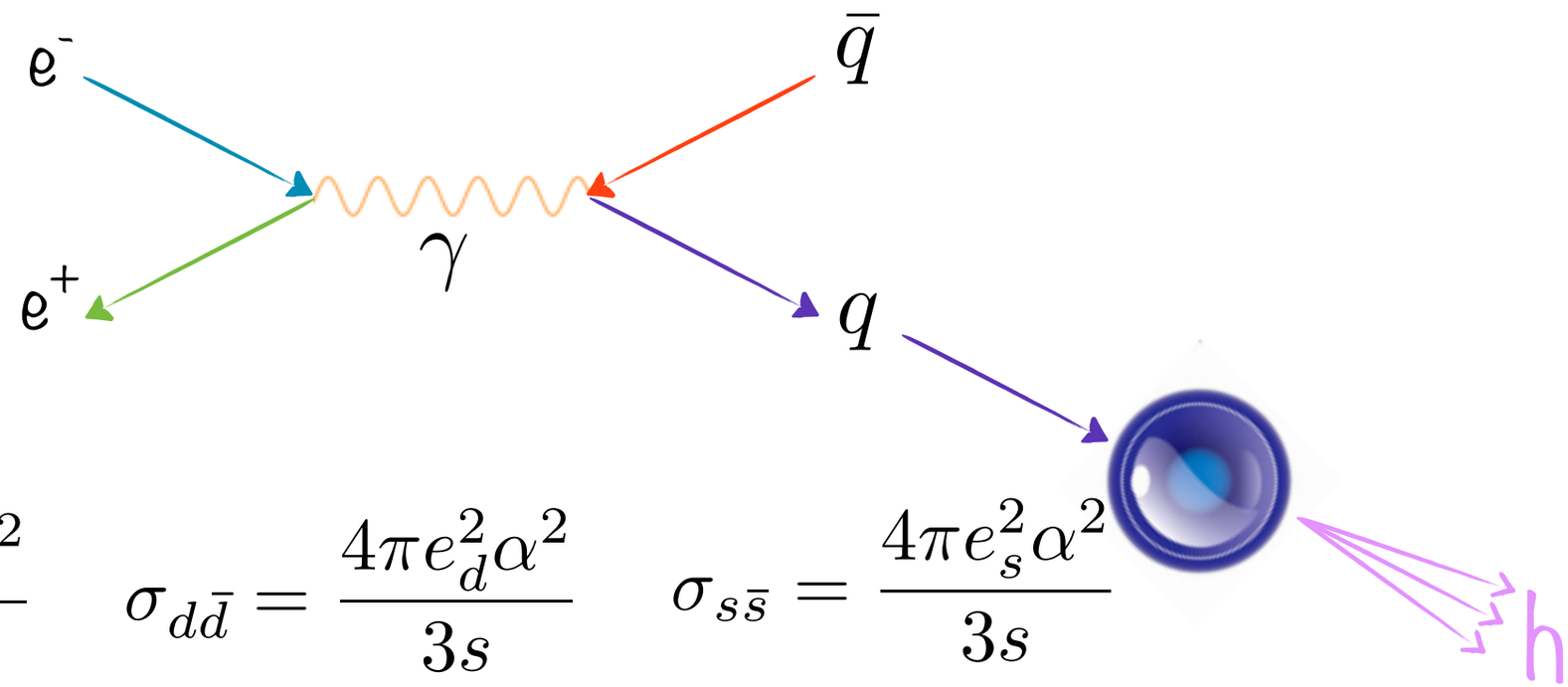



$q = u,\ d,\ s$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$



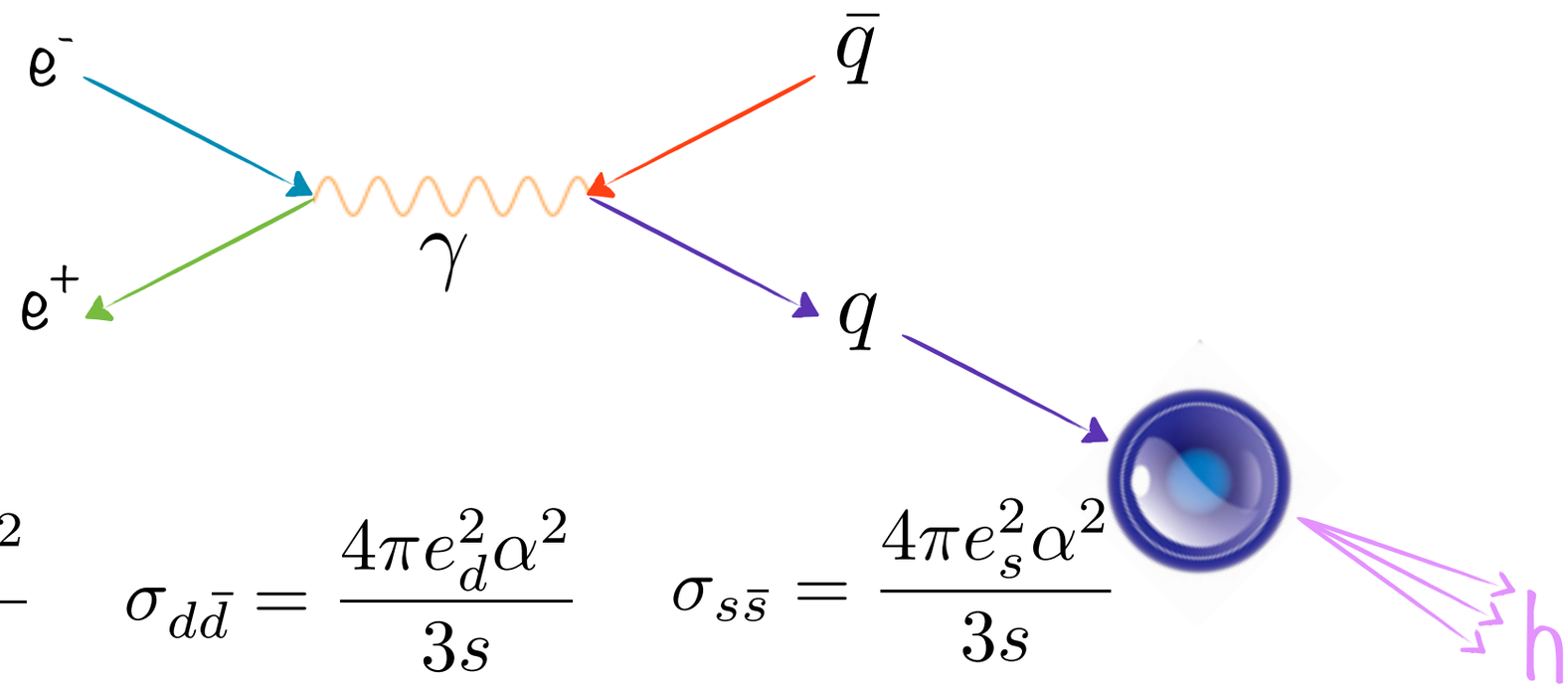

$q = u,\ d,\ s$

$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$




$q = u,\ d,\ s$

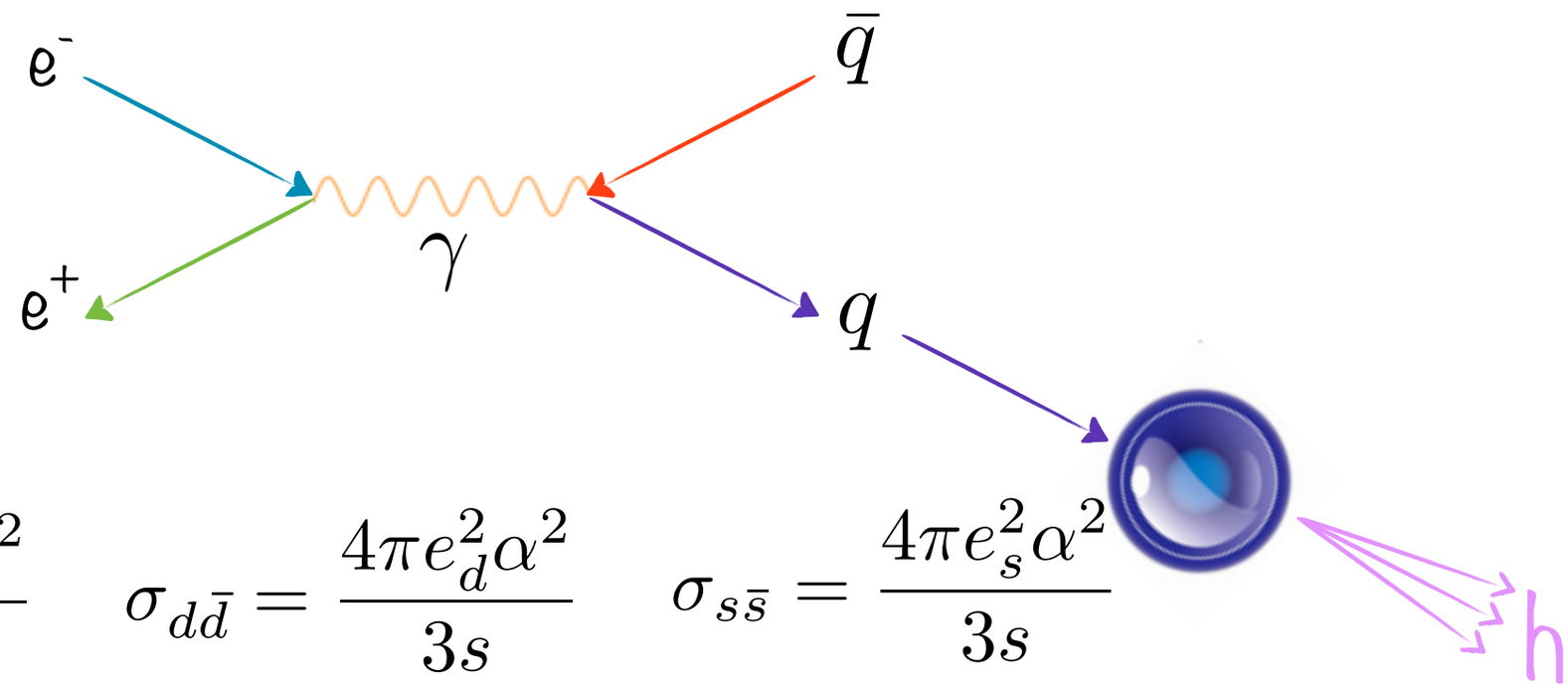
$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

$e_u = 2/3;$
$e_d = -1/3;$
$e_s = 2/3;$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$




$q = u,\ d,\ s$

$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

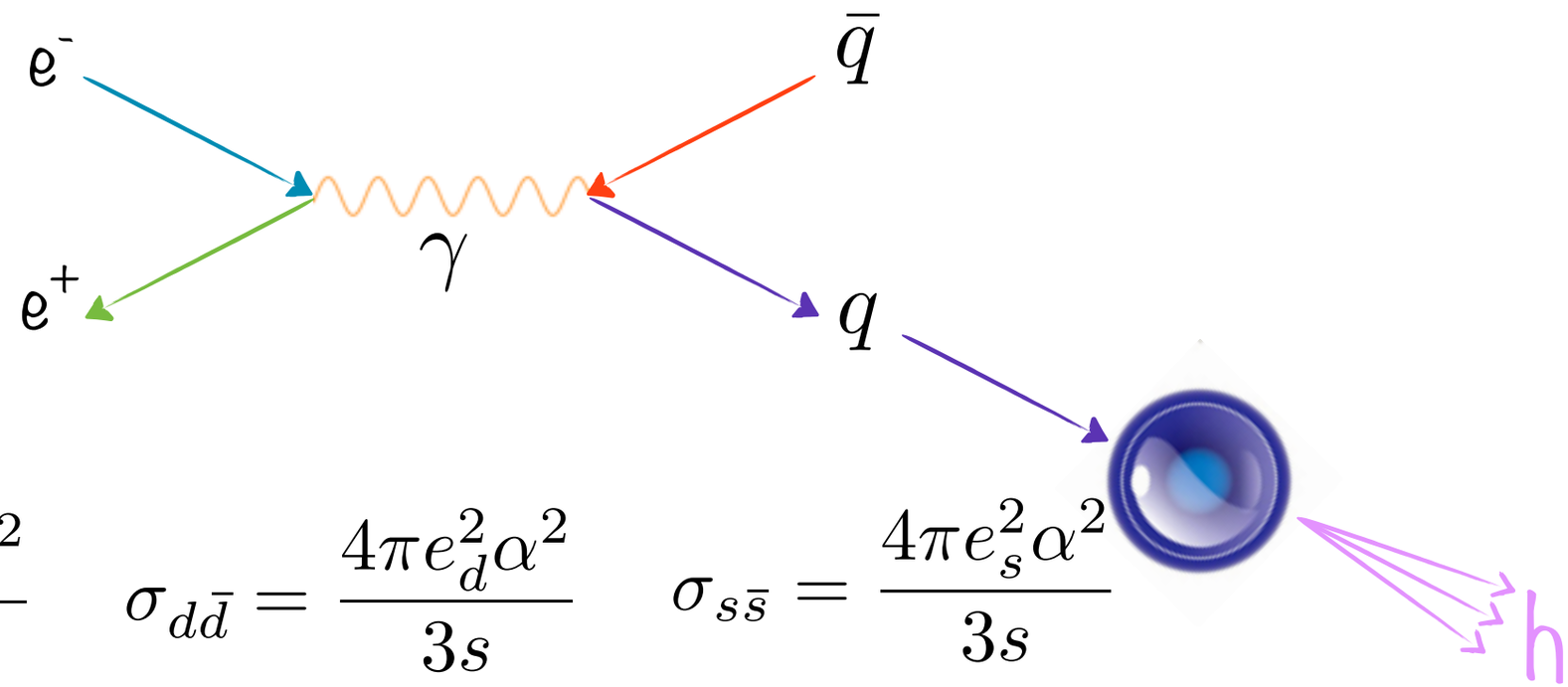
$e_u = 2/3;$
$e_d = -1/3;$
$e_s = 2/3;$

But! we cannot distinguish the quark flavor!
We measure their sum!

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$




$q = u,\ d,\ s$

$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

$e_u = 2/3;$
$e_d = -1/3;$
$e_s = 2/3;$

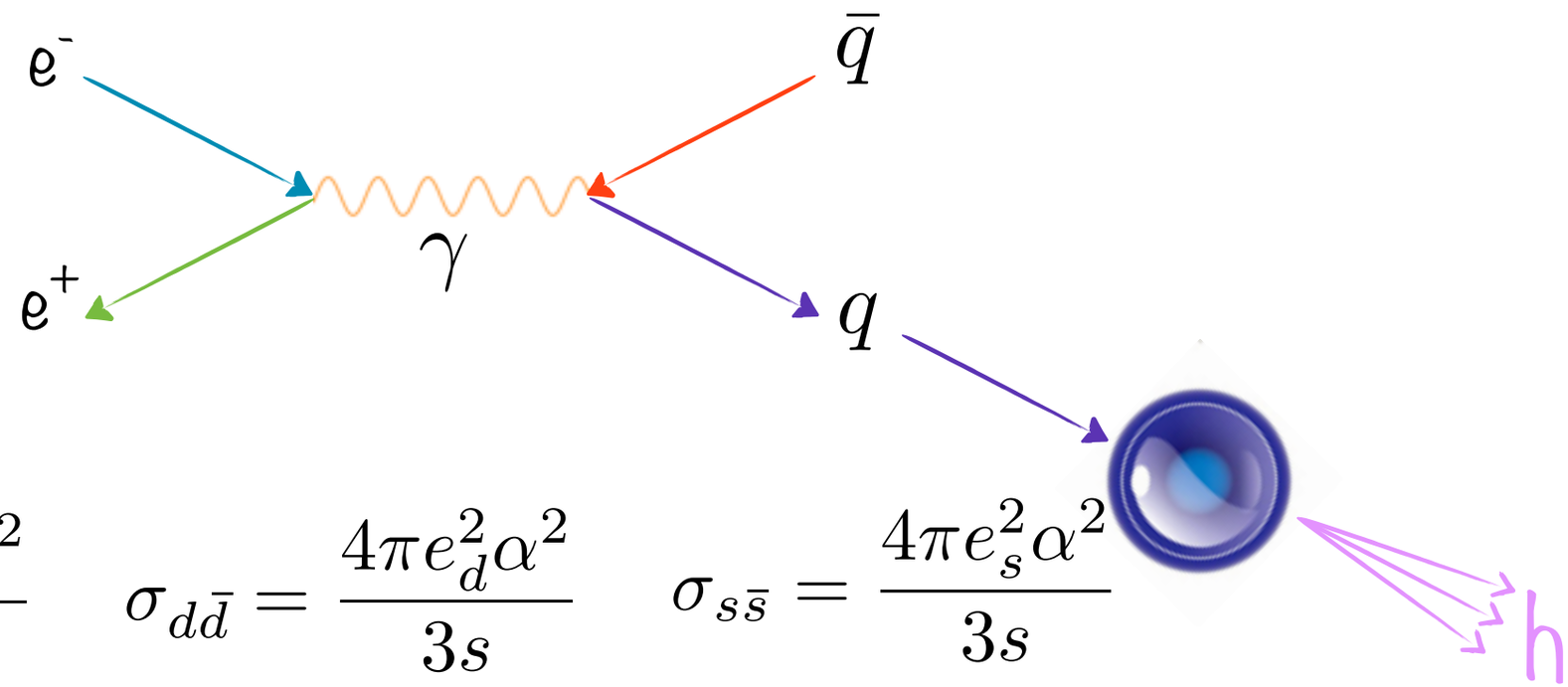
But! we cannot distinguish the quark flavor!
We measure their sum!

$\times 3$ (color charge!) $u\bar{u}$ $u\bar{u}$ $u\bar{u}$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$




$q = u,\ d,\ s$

$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

$e_u = 2/3;$
$e_d = -1/3;$
$e_s = 2/3;$

But! we cannot distinguish the quark flavor!
We measure their sum!

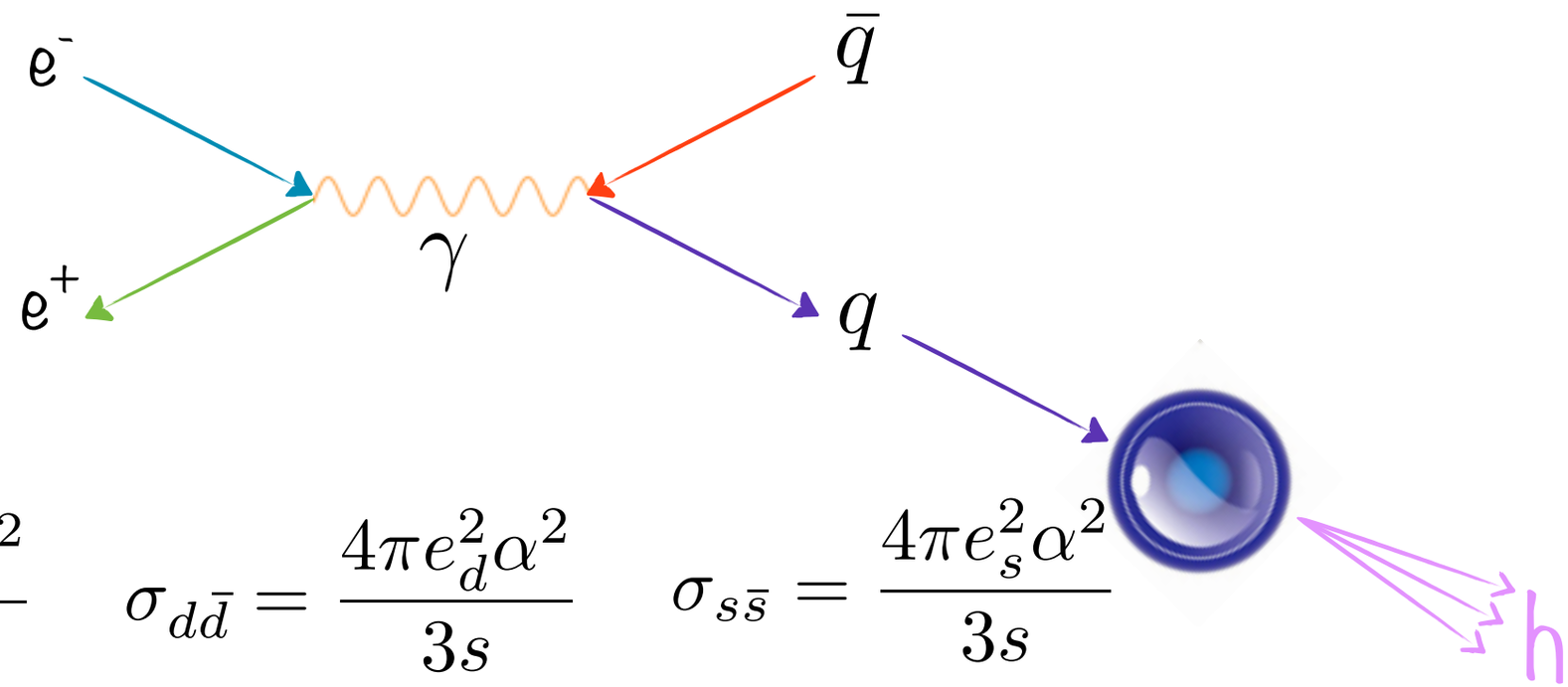
$\times 3$ (color charge!) $u\bar{u}$ $u\bar{u}$ $u\bar{u}$

$$\sigma = 3 \sum_{q=u,d,s} \frac{4\pi e_q^2 \alpha^2}{3s} = 3\frac{4\pi\alpha^2}{3s} \sum_{q=u,d,s} e_q^2$$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$




$q = u,\ d,\ s$

$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

$e_u = 2/3;$
$e_d = -1/3;$
$e_s = 2/3;$

But! we cannot distinguish the quark flavor!
We measure their sum!

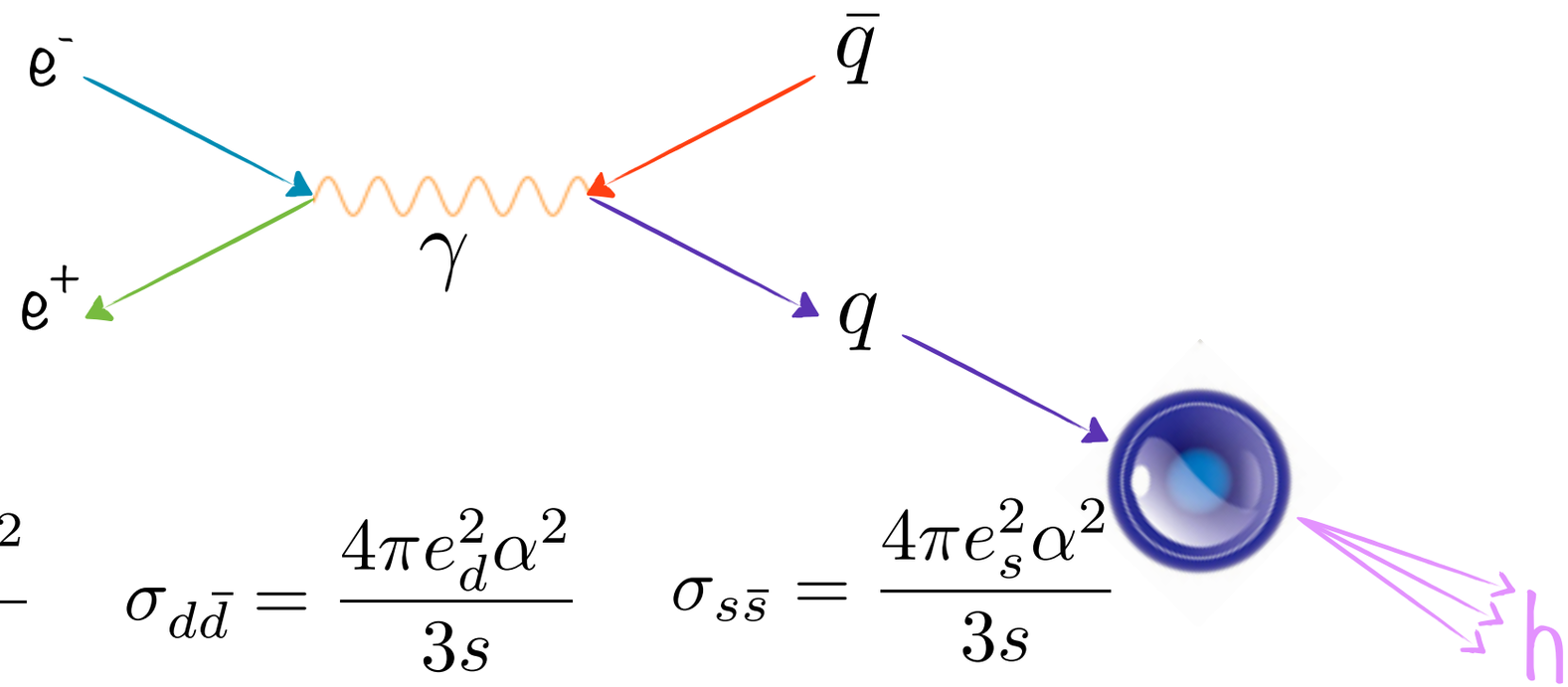
$\times 3$ (color charge!) $u\bar{u}$ $u\bar{u}$ $u\bar{u}$

$$\sigma = 3 \sum_{q=u,d,s} \frac{4\pi e_q^2 \alpha^2}{3s} = 3\frac{4\pi\alpha^2}{3s} \sum_{q=u,d,s} e_q^2$$

# $e^+e^-$ annihilation

Also pure QED!
($Z_0$ neglected)

$$e^+e^- \to q\,\bar{q} \to hX$$




$q = u,\ d,\ s$

$$\sigma_{u\bar{u}} = \frac{4\pi e_u^2 \alpha^2}{3s} \qquad \sigma_{d\bar{d}} = \frac{4\pi e_d^2 \alpha^2}{3s} \qquad \sigma_{s\bar{s}} = \frac{4\pi e_s^2 \alpha^2}{3s}$$

$e_u = 2/3;$
$e_d = -1/3;$
$e_s = 2/3;$

But! we cannot distinguish the quark flavor!
We measure their sum!

$\times 3$ (color charge!) $u\bar{u}$ $u\bar{u}$ $u\bar{u}$

$$\sigma = 3 \sum_{q=u,d,s} \frac{4\pi e_q^2 \alpha^2}{3s} = 3\frac{4\pi\alpha^2}{3s} \sum_{q=u,d,s} e_q^2$$

Experimental access to color numbers!
Experimental access to quark electrical charges!

# $e^+e^-$ annihilation

$$\frac{\sigma_{e^+e^-\to hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}} = N_c \sum_q e_q^2$$

$N_c = 3$

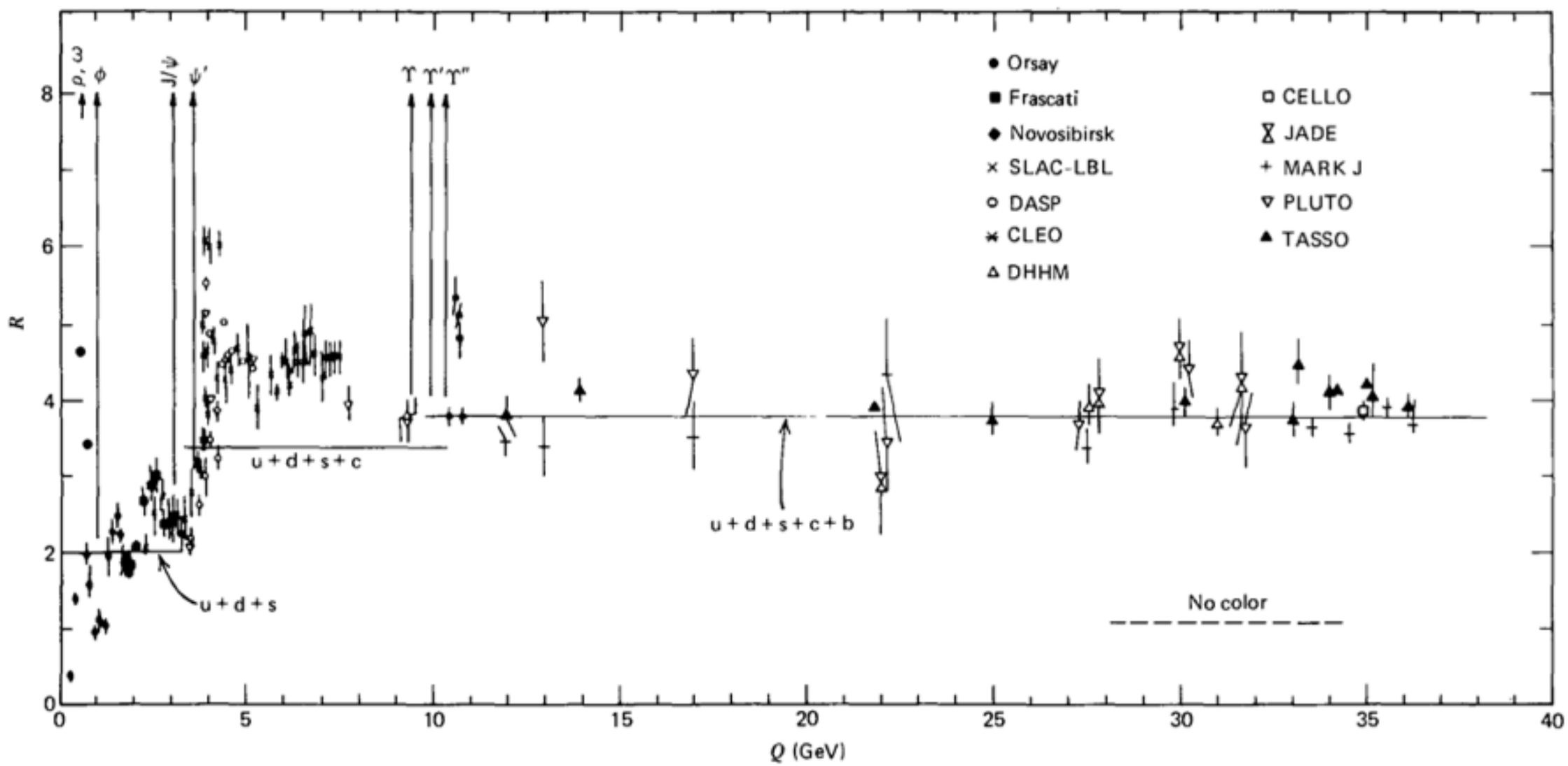
$q = u,\, d,\, s$ $\qquad 3[(2/3)^2 + (1/3)^2 + (2/3)^2] = 2$

$q = u,\, d,\, s,\, c$ $\qquad 2 + 3(2/3)^2 = 10/3$

$q = u,\, d,\, s,\, c,\, b$ $\qquad 10/3 + 3(1/3)^2 = 11/3$

# $e^+e^-$ annihilation

$$\frac{\sigma_{e^+e^-\to hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}} = N_c \sum_q e_q^2$$

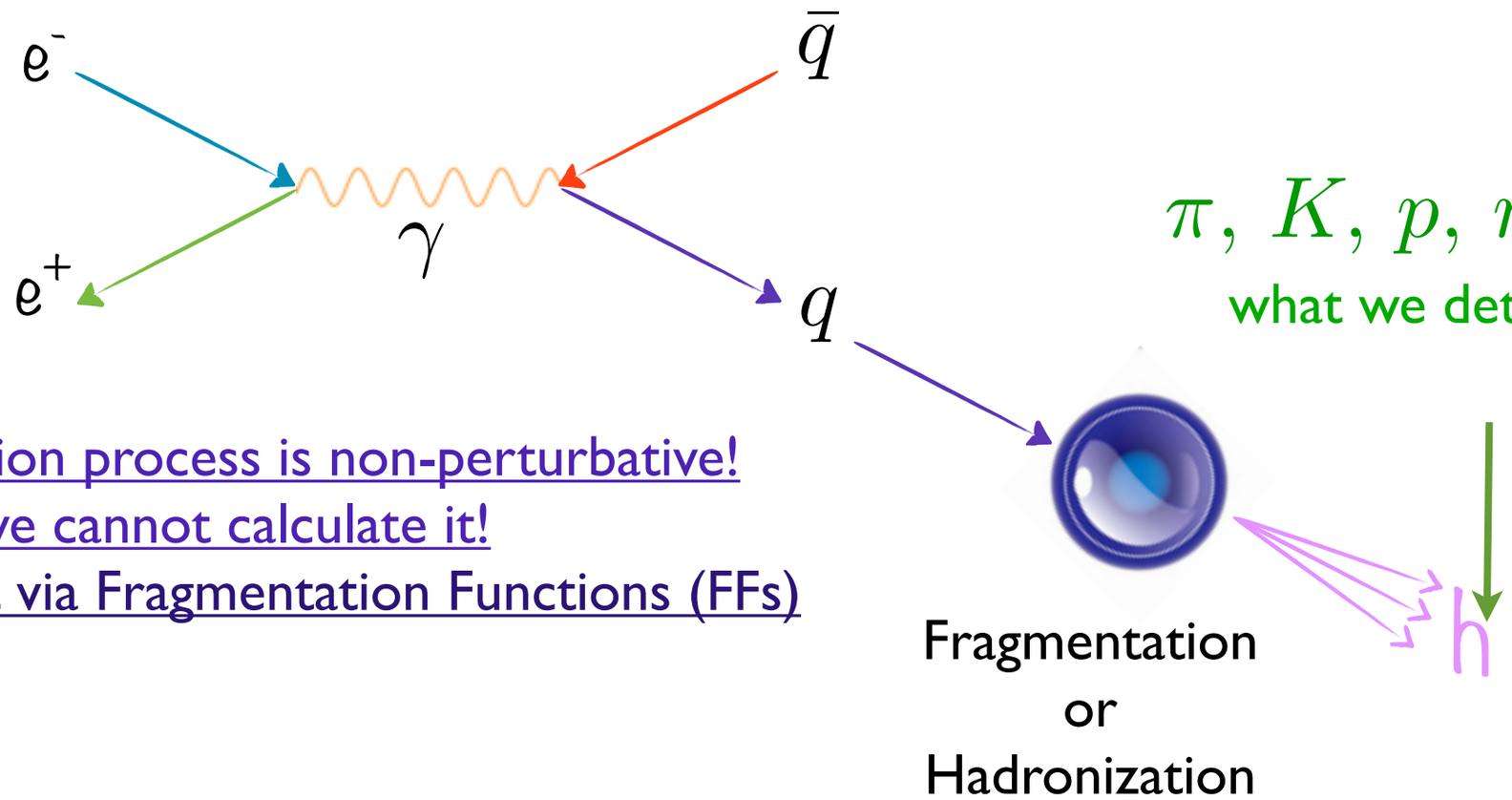



from Hazeln-Martin

# Fragmentation process

## or how do the hadrons get formed?

$$e^+e^- \to q\,\bar{q} \to hX$$

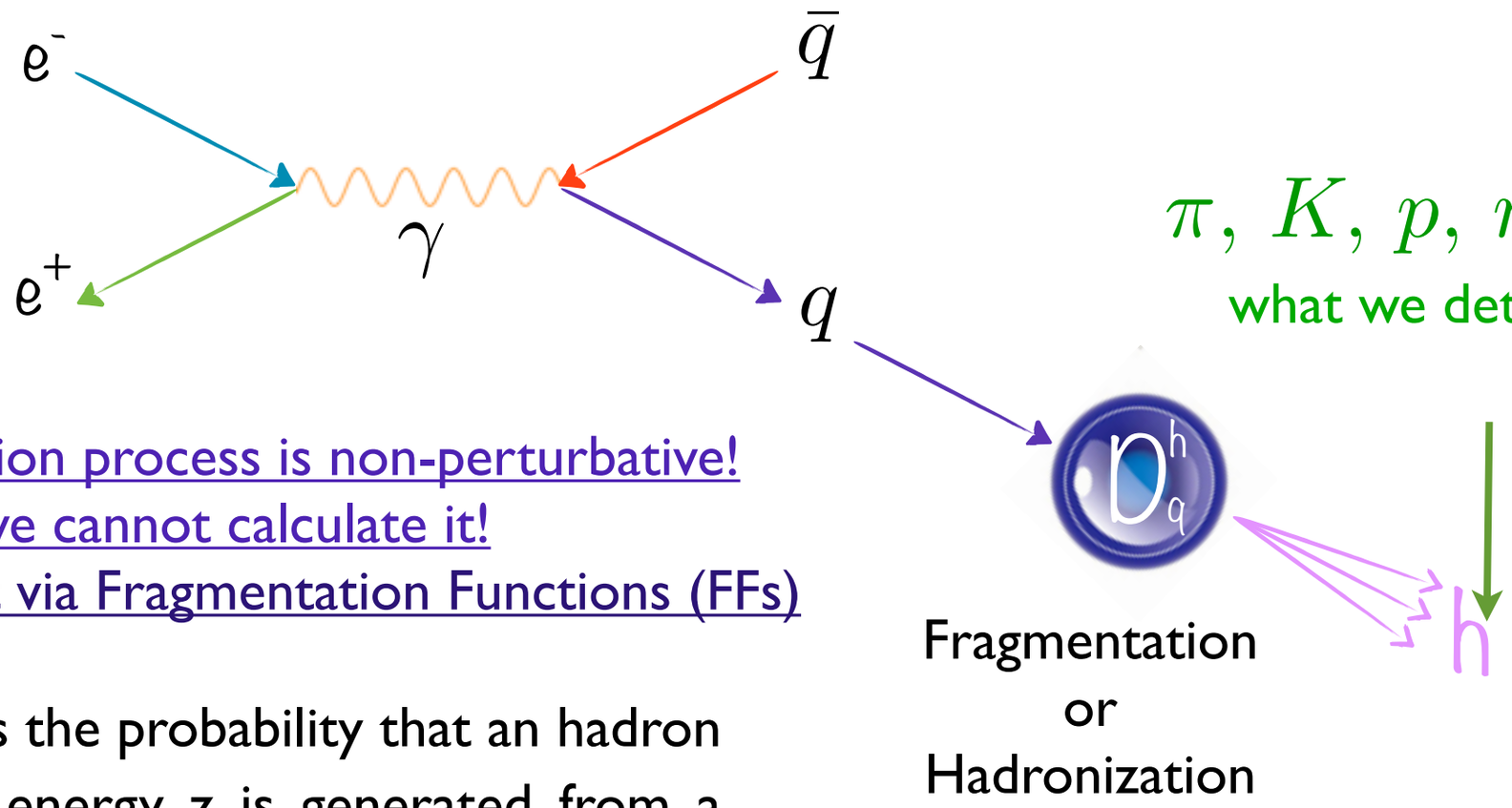



The fragmentation process is non-perturbative!
=> we cannot calculate it!
We parametrize it via Fragmentation Functions (FFs)

# Fragmentation process

## or how do the hadrons get formed?

$$e^+e^- \to q\,\bar{q} \to hX$$




The fragmentation process is non-perturbative!
=> we cannot calculate it!
We parametrize it via Fragmentation Functions (FFs)

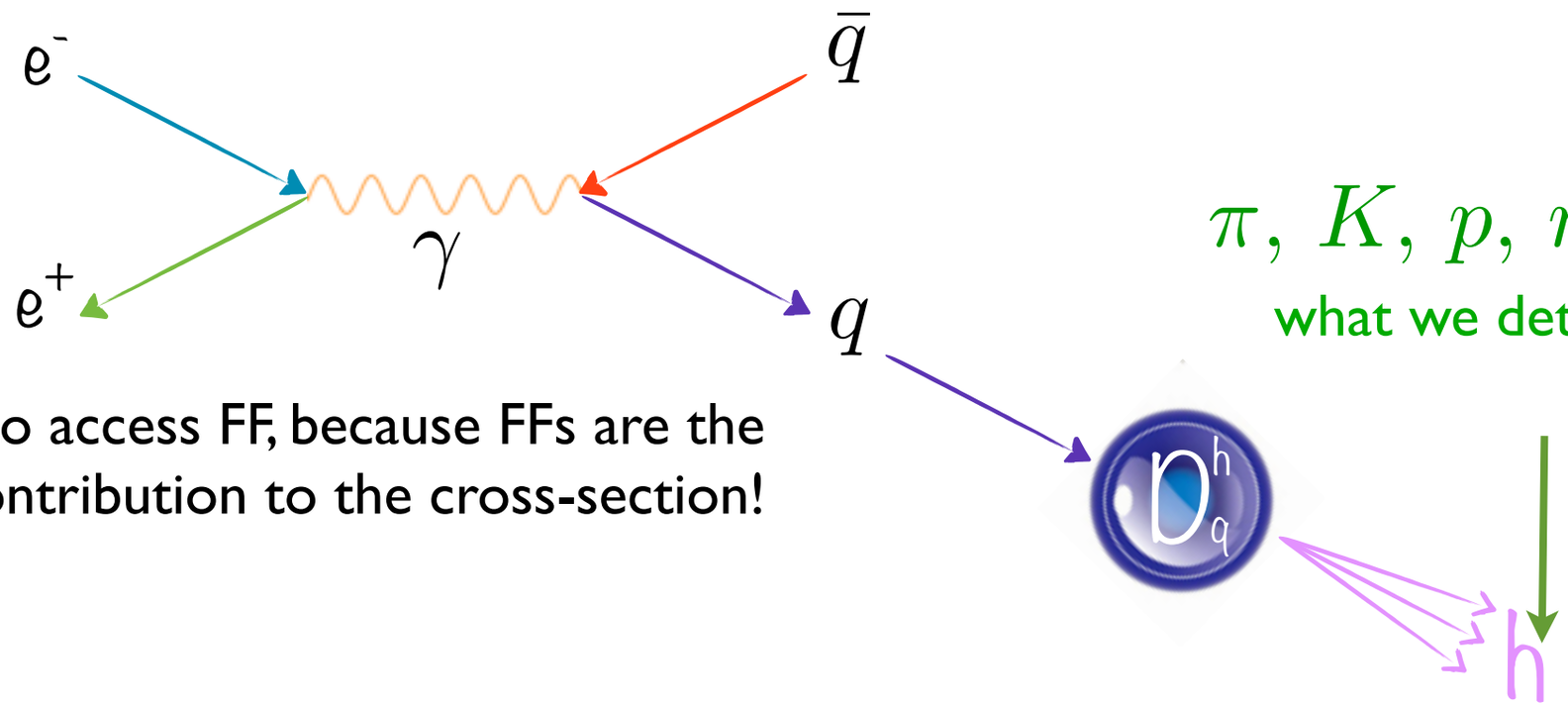
$D_q^h(z)$ is the probability that an hadron h with energy z is generated from a parton q

$$z \equiv \frac{E_h}{E_q} = \frac{E_h}{E_b} = \frac{2E_h}{Q}$$

# Fragmentation process

## or how do the hadrons get formed?

$$e^+e^- \to q\,\bar{q} \to hX$$



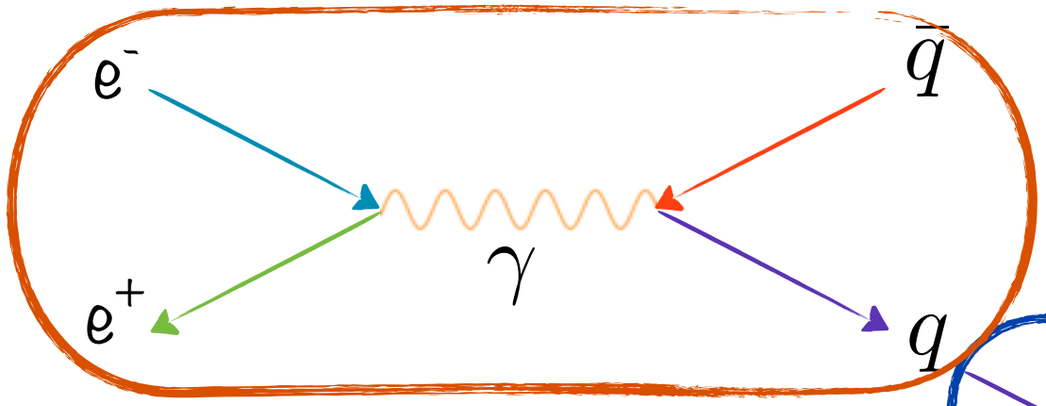

$e^+e^-$ is the cleanest way to access FF, because FFs are the only non-perturbative contribution to the cross-section!

$$\sigma^{e^+e^-\to hX} \propto \sum_q \underbrace{\sigma^{e^+e^-\to q\bar{q}}}_{\text{elementary cross-section}} \times \underbrace{(D_q^h + D_{\bar{q}}^h)}_{\text{FF}}$$

# Fragmentation process

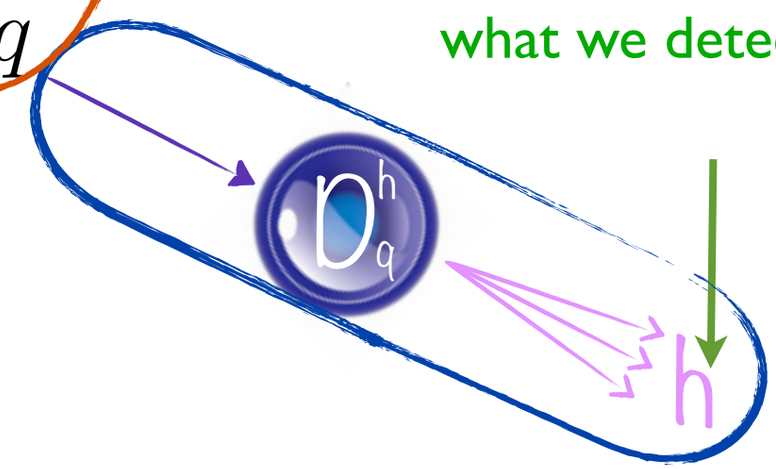
## or how do the hadrons get formed?

$$e^+e^- \to q\,\bar{q} \to hX$$




$\pi,\ K,\ p,\ \eta,\ \ldots$

what we detect




$e^+e^-$ is the cleanest way to access FF, because FFs are the only non-perturbative contribution to the cross-section!

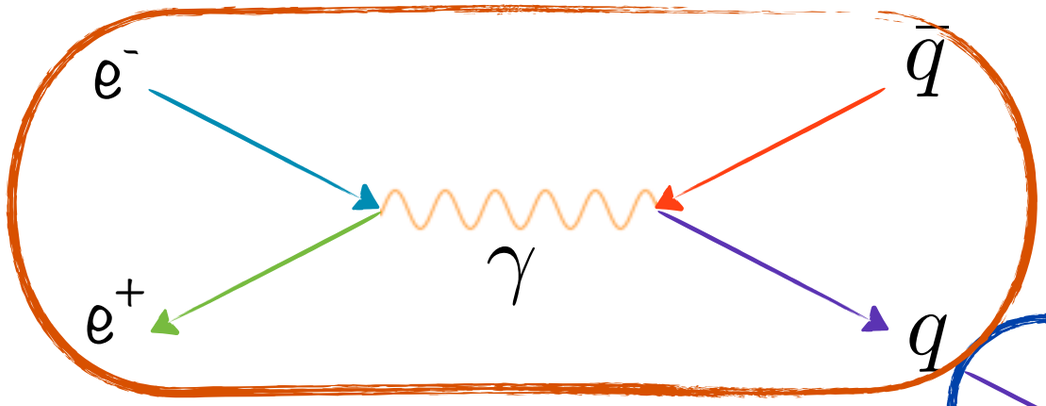
Factorization of the cross section!

$$\sigma^{e^+e^-\to hX} \propto \sum_q \underbrace{\sigma^{e^+e^-\to q\bar{q}}}_{\text{elementary cross-section}} \times \underbrace{(D_q^h + D_{\bar{q}}^h)}_{\text{FF}}$$

# Fragmentation process

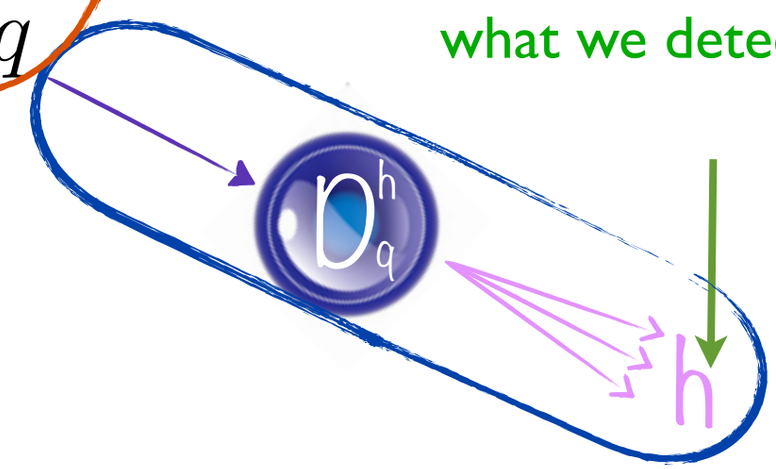
## or how do the hadrons get formed?

$$e^+e^- \to q\,\bar{q} \to hX$$




$\pi,\ K,\ p,\ \eta,\ \ldots$

what we detect




$e^+e^-$ is the cleanest way to access FF, because FFs are the only non-perturbative contribution to the cross-section!

Isospin & charge Symmetries

$$\sigma^{e^+e^-\to\pi^+X} = \sigma^{e^+e^-\to\pi^-X}$$

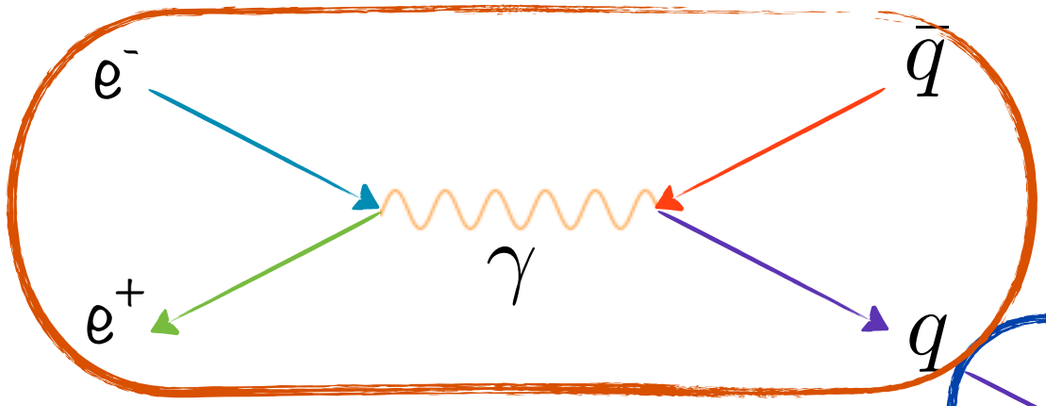
Factorization of the cross section!

$$\sigma^{e^+e^-\to hX} \propto \sum_q \underbrace{\sigma^{e^+e^-\to q\bar{q}}}_{\text{elementary cross-section}} \times \underbrace{(D_q^h + D_{\bar{q}}^h)}_{\text{FF}}$$

# Fragmentation process

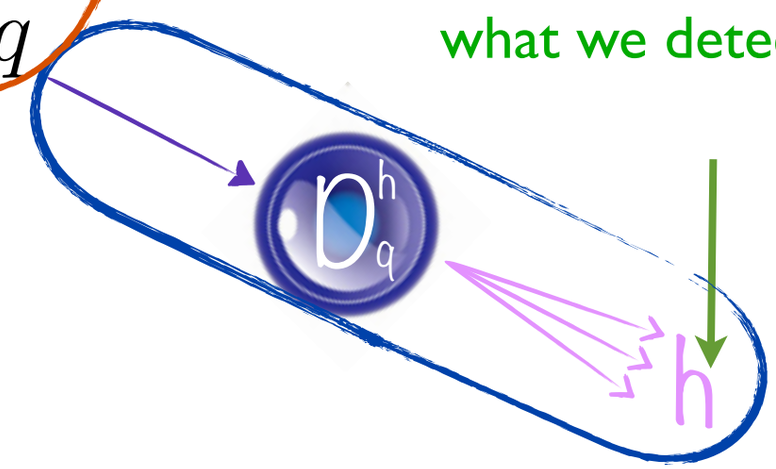
## or how do the hadrons get formed?

$$e^+e^- \to q\,\bar{q} \to hX$$




$\pi,\ K,\ p,\ \eta,\ \ldots$

what we detect




$e^+e^-$ is the cleanest way to access FF, because FFs are the only non-perturbative contribution to the cross-section!

Isospin & charge Symmetries

$$\sigma^{e^+e^-\to\pi^+X} = \sigma^{e^+e^-\to\pi^-X}$$

Factorization of the cross section!

$$\sigma^{e^+e^-\to hX} \propto \sum_q \sigma^{e^+e^-\to q\bar{q}} \times (D_q^h + D_{\bar{q}}^h)$$

elementary cross-section

FF

LO, NLO: $D_q^h\ D_{\bar{q}}^h$

NLO: $D_g^h$

# Fragmentation process

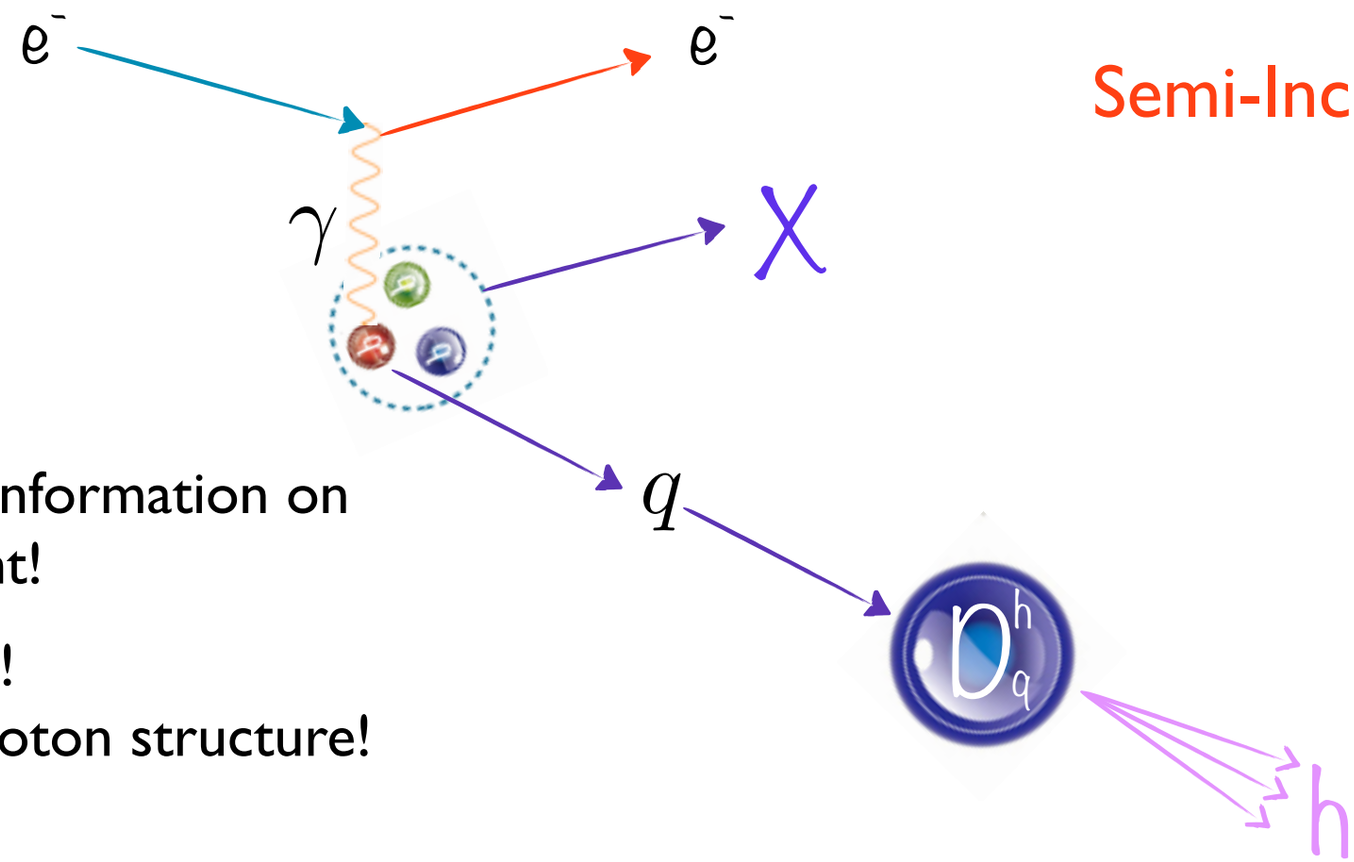
## or how do the hadrons get formed?

Knowing the FFs can provide information on quark confinement!

# Fragmentation process

## or how do the hadrons get formed?

$$lp \to lhX$$




Semi-Inclusive DIS

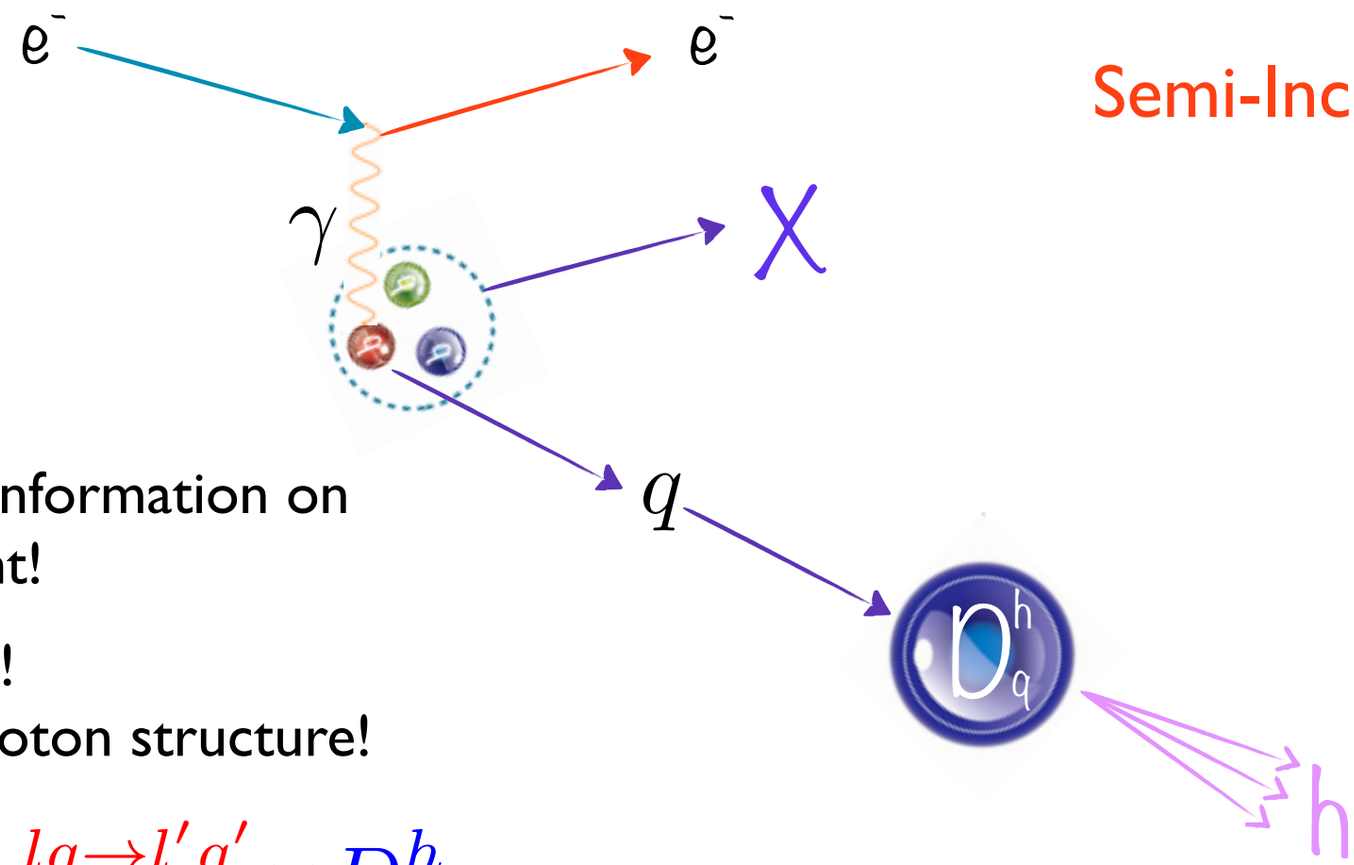
Knowing the FFs can provide information on quark confinement!

FFs are universal!
=> can be used to study the proton structure!

# Fragmentation process

## or how do the hadrons get formed?

$$lp \to lhX$$




Semi-Inclusive DIS

Knowing the FFs can provide information on quark confinement!

FFs are universal!
=> can be used to study the proton structure!

$$\sigma^{l\,p\to l'\,hX} \propto \sum_q f_q \times \sigma^{lq\to l'\,q'} \times D_q^h$$

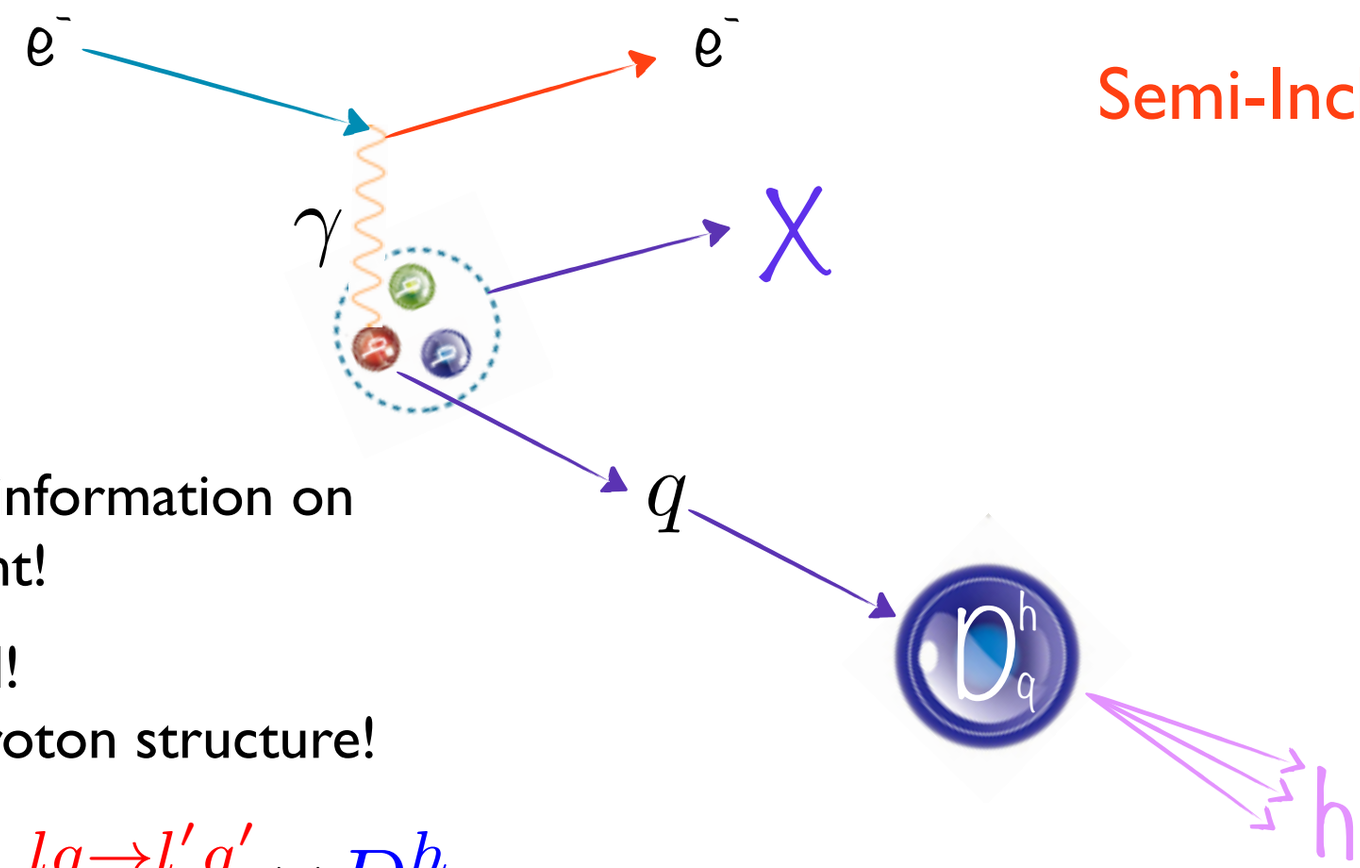
PDF — elementary cross-section — FF

Two non-perturbative contributions to the cross-section!

# Fragmentation process

## or how do the hadrons get formed?

$$lp \to lhX$$




Semi-Inclusive DIS

Knowing the FFs can provide information on quark confinement!

FFs are universal!
=> can be used to study the proton structure!

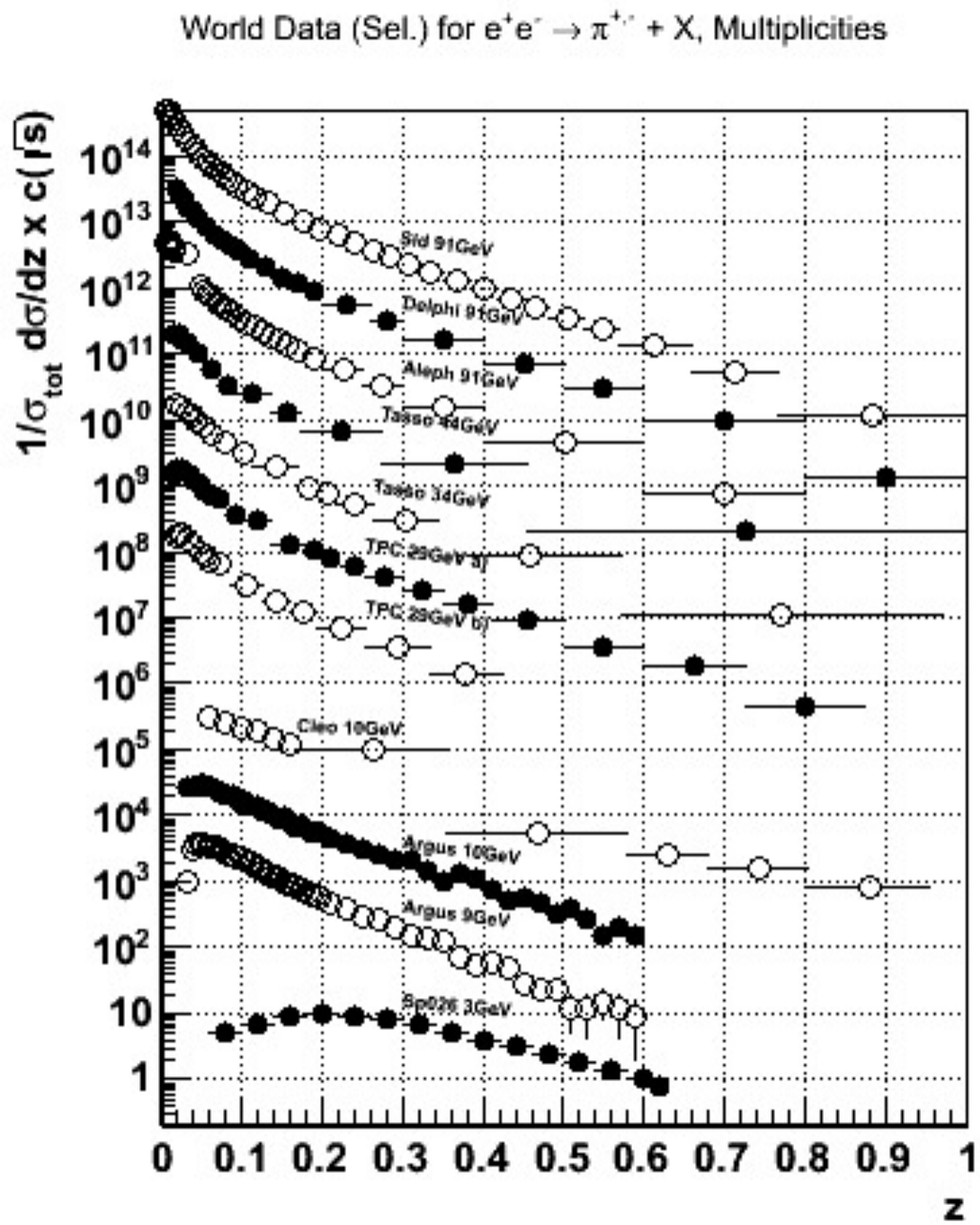
$$\sigma^{l\,p\to l'\,hX} \propto \sum_q f_q \times \sigma^{lq\to l'\,q'} \times D_q^h$$

PDF — elementary cross-section — FF

$$A_{UT}^h = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\uparrow\Downarrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\uparrow\Downarrow}} \propto D_q^h$$

Two non-perturbative contributions to the cross-section!

# $e^+e^-$ data




2007: First unpolarized FF extraction with estimated uncertainties!

**Hirai, Kumano, Nagai, Sudoh**
**Phys. Rev. D 75, 094009 (2007)**

Global analises:
e+e-, SIDIS, pp: (including uncertainties)

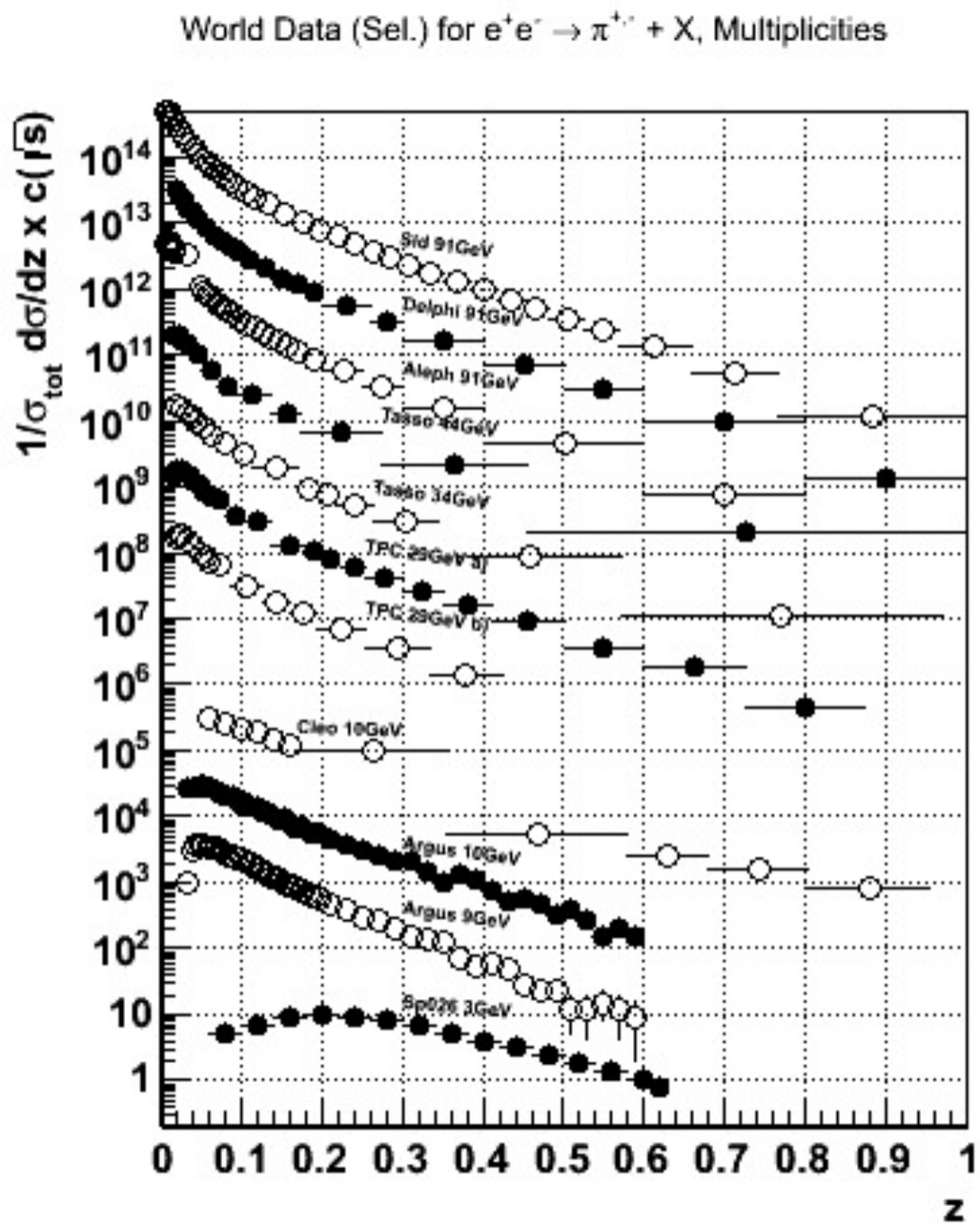
**de Florian, Sassot, Stratmann**
**Phys. Rev. D 75, 114010 (2007) and**
**Phys. Rev D 76, 074033 (2007)**

**Epele, Llubaroff, Sassot, Stratmann**
**arXiv:1209.3240 [hep-ph]**

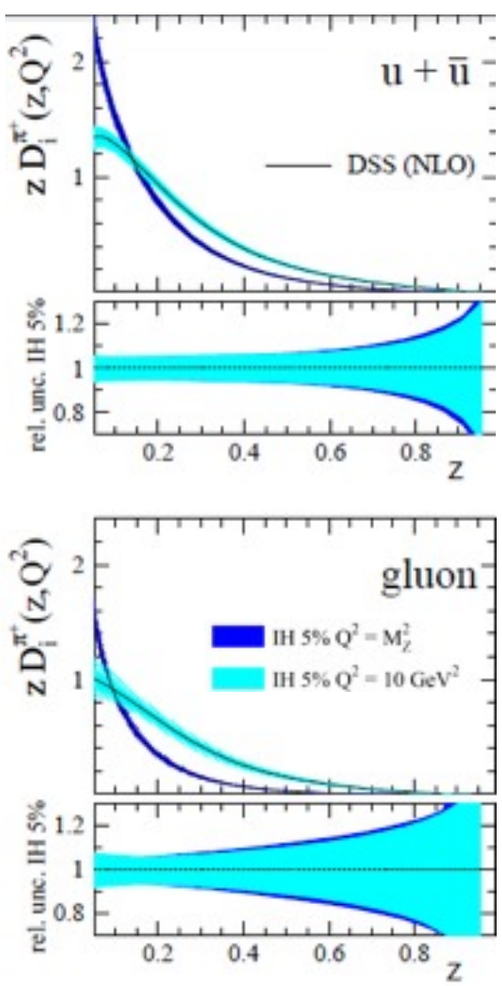
e+e-, pp:

**Albino, Kniehl, Kramer**
**Nucl. Phys. B 803, 42 (2008)**

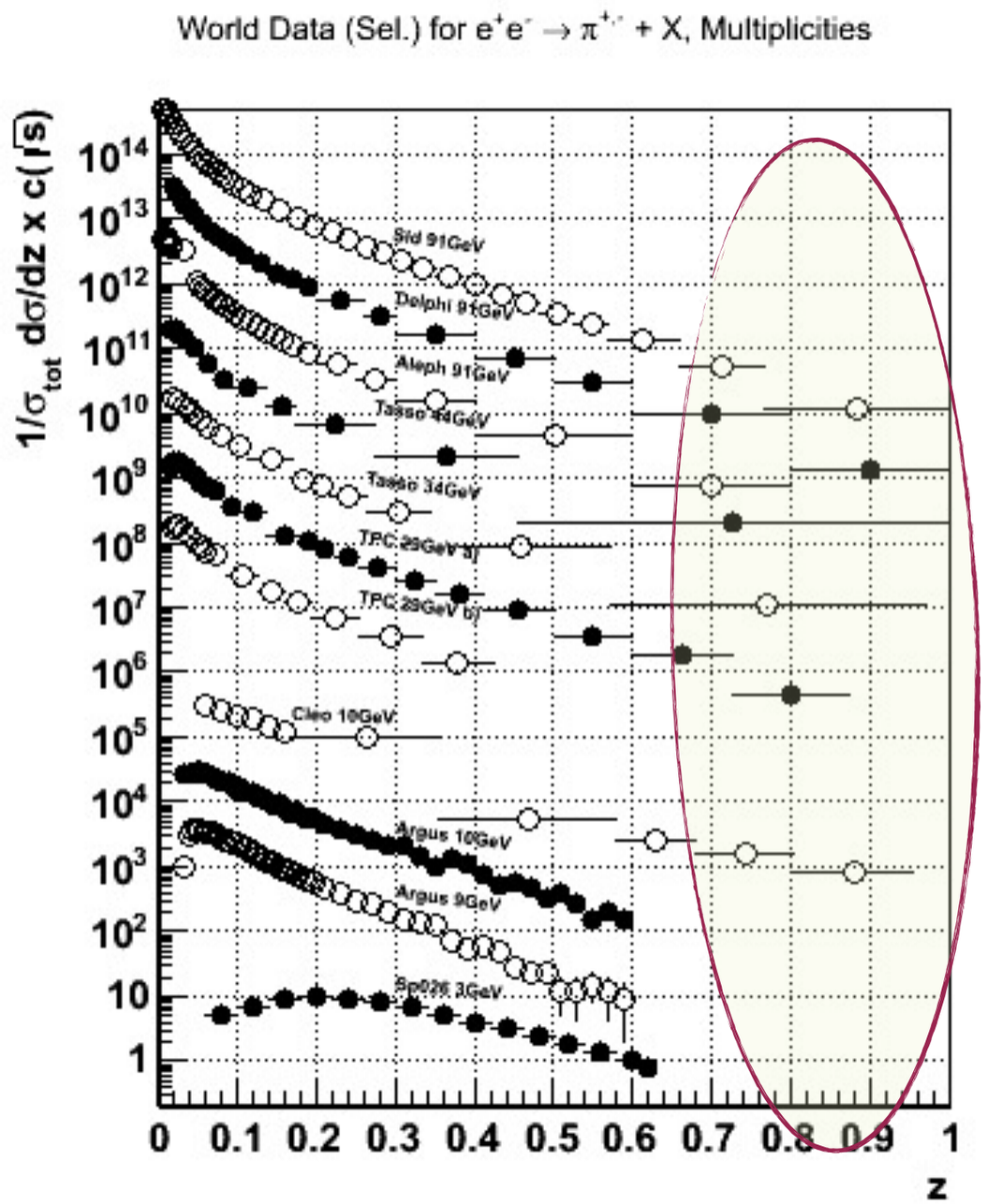
# $e^+e^-$ data



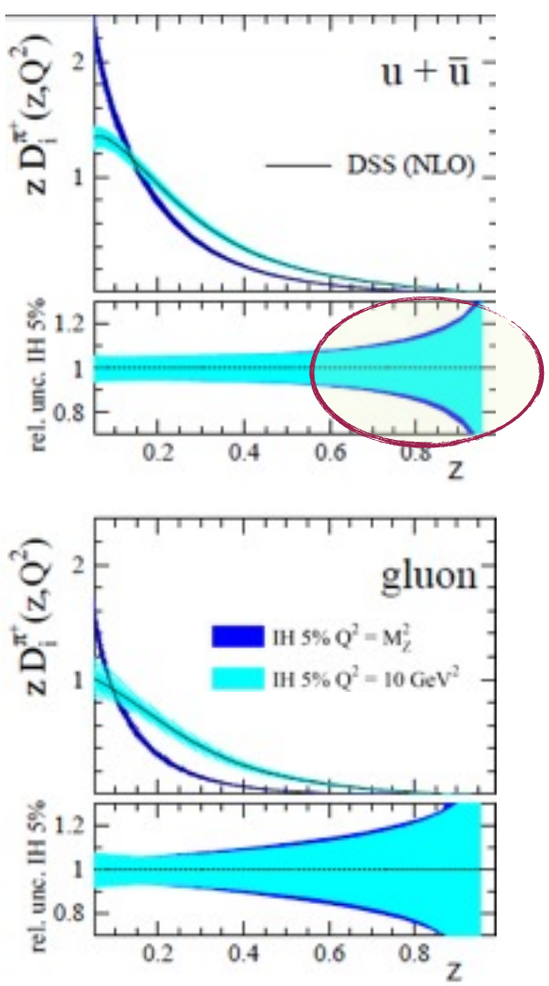

**Epele, Llubaroff, Sassot, Stratmann**
**arXiv:1209.3240 [hep-ph]**



# $e^+e^-$ data

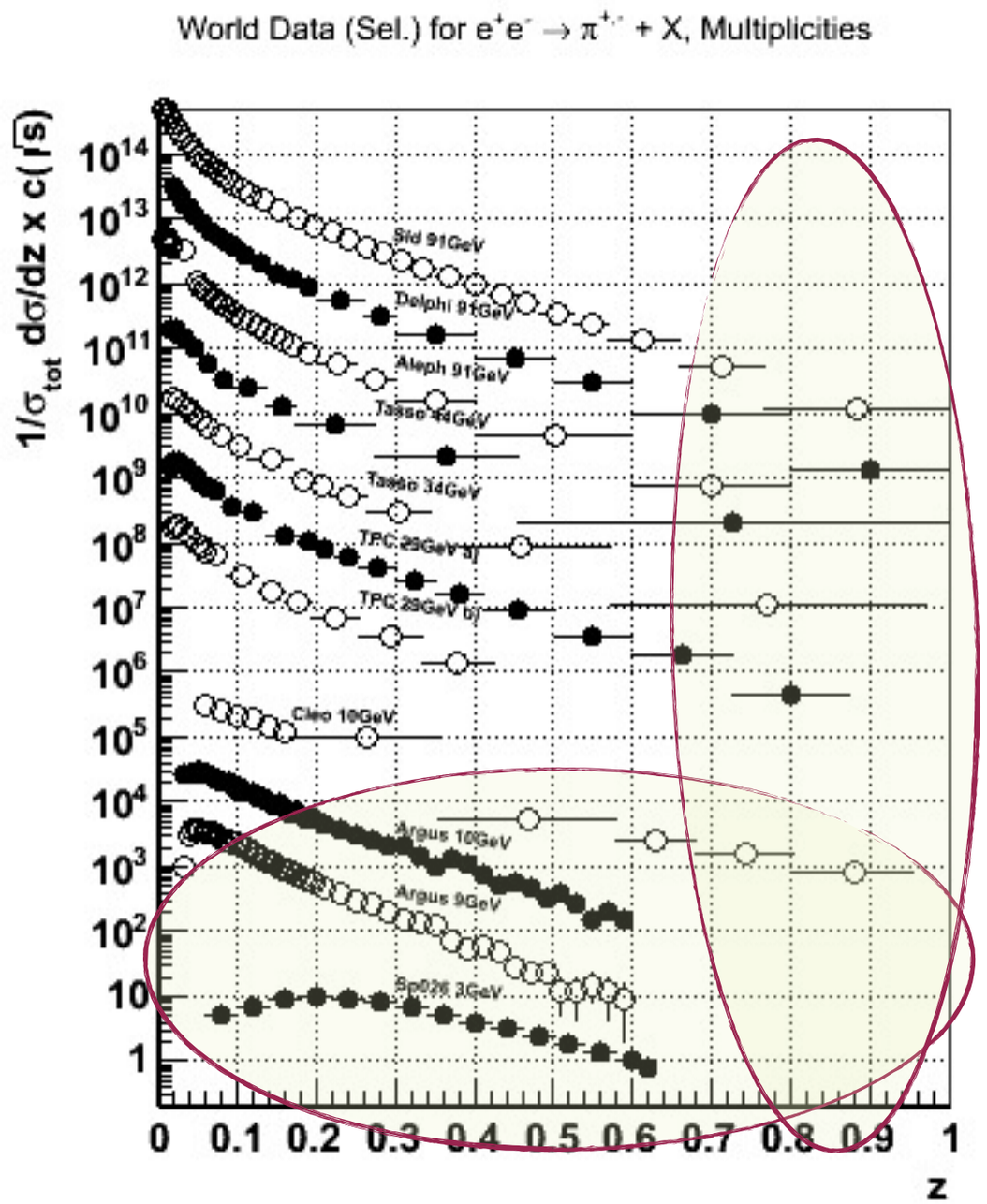



**Epele, Llubaroff, Sassot, Stratmann**
**arXiv:1209.3240 [hep-ph]**

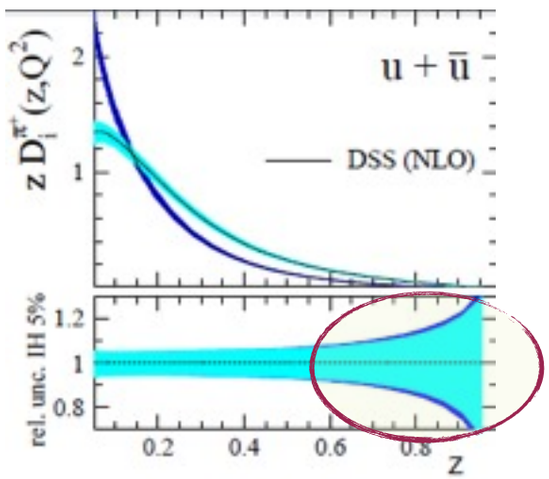



Few data at high z

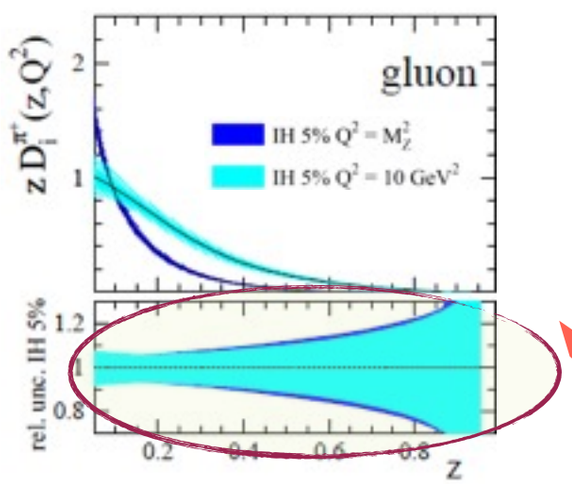
# $e^+e^-$ data




**Epele, Llubaroff, Sassot, Stratmann**
**arXiv:1209.3240 [hep-ph]**

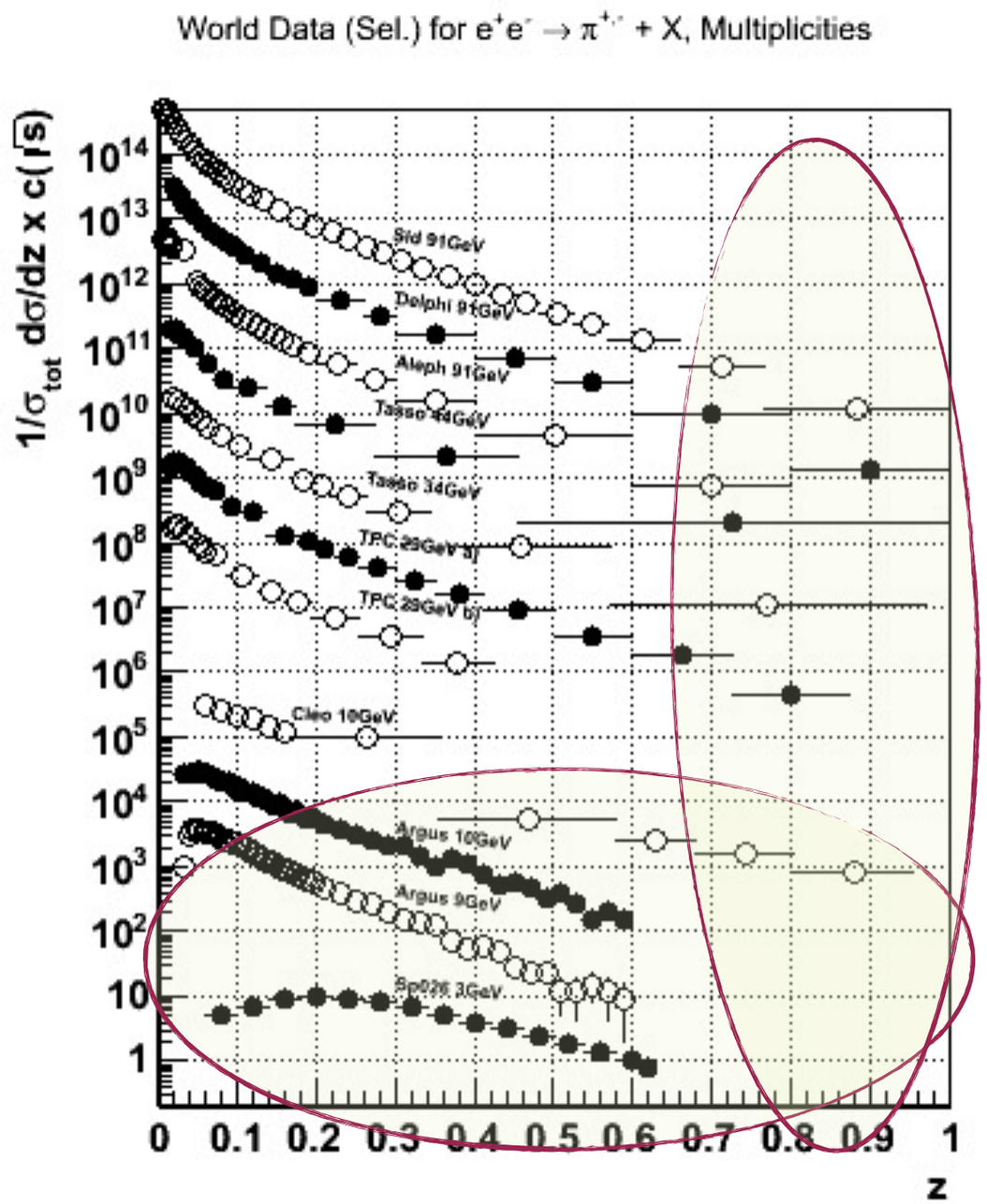



Few data at high z

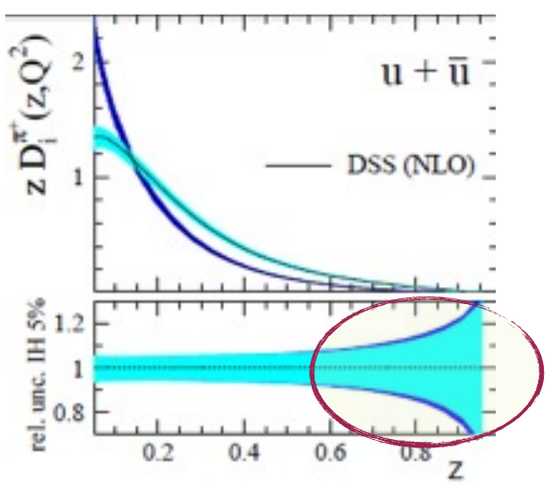



Few data at low energy

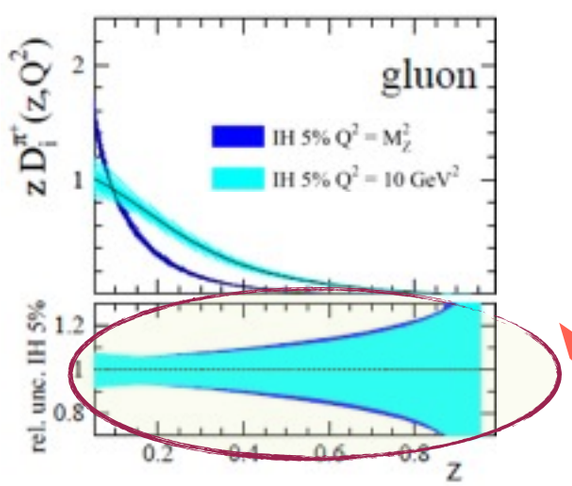
# $e^+e^-$ data




**Epele, Llubaroff, Sassot, Stratmann**
**arXiv:1209.3240 [hep-ph]**




Few data at high z

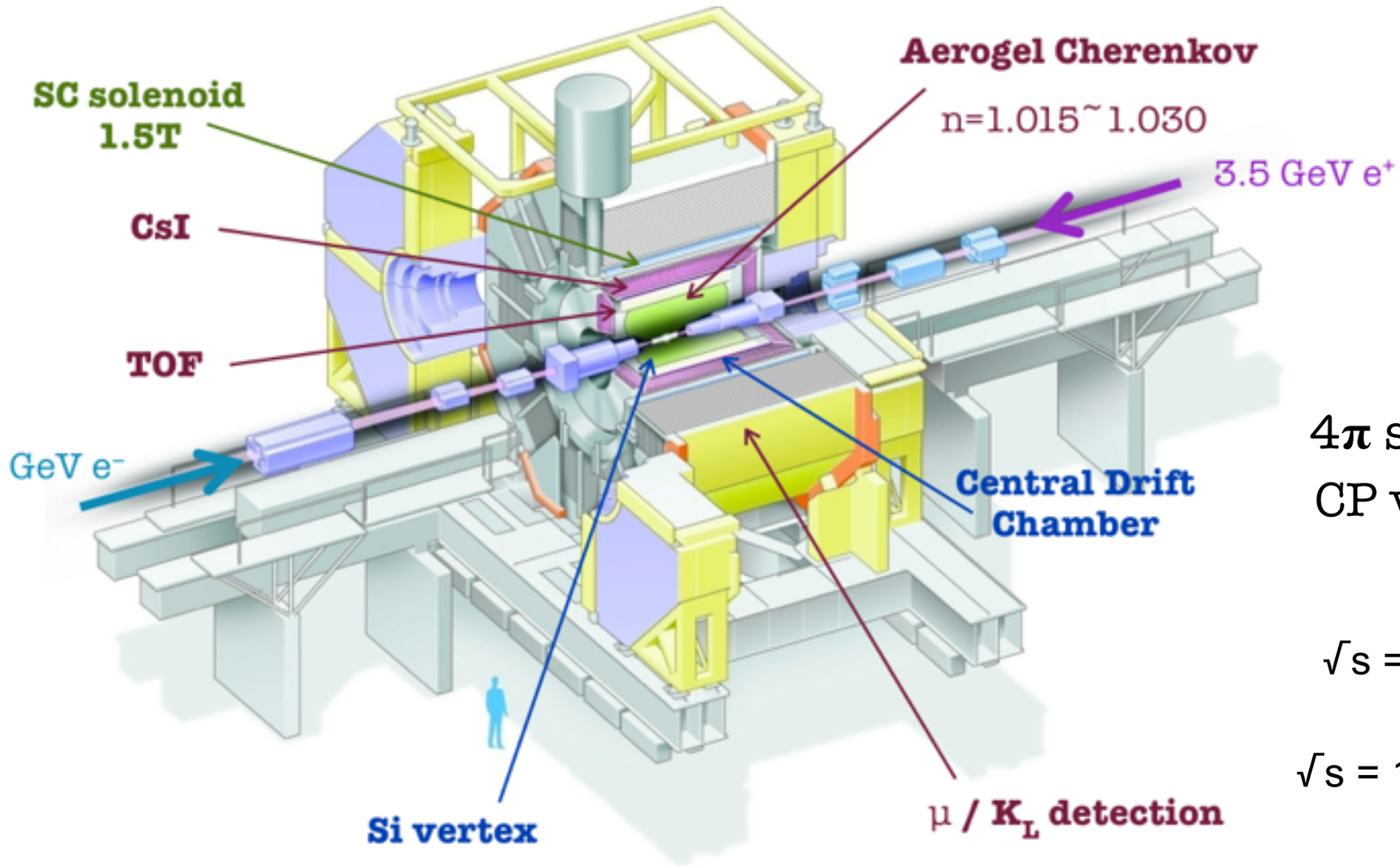



Few data at low energy

# BELLE @ KEKB

KEKB
Harbin
哈尔滨
黑龙江
Sapporo
札幌
Aomori
青森
Morioka
盛岡
Akita
秋田
Sea of Japan
日本
(Japan)
Niigata
新潟
Sendai
仙台
Fukushima
福島
Nagano
長野
Tottori
鳥取
Nagoya
名古屋
Chiba
千葉
Shizuoka
静岡
Osaka
大阪
Hiroshima
広島
Fukuoka
福岡
Saga
佐賀
Kochi
高知
Kumamoto
熊本
Miyazaki
宮崎
Kagoshima
鹿児島
(South Korea)
Daejeon
대전
Daegu
대구
Gwangju
광주
Busan
부산
山东
Nanjing
南京
江苏
Shanghai
上海
安徽
Hangzhou
杭州
浙江
East
China Sea

# BELLE @ KEKB




KEKB:
Asymmetric e+ e- collider
(3.5 / 8 GeV)

Belle spectrometer:
$4\pi$ spectrometer optimized for
CP violation in B-meson decay

On resonance:
$\sqrt{s}$ = 10.58 GeV (e+ e- → $\Upsilon(4S) \to B\bar{B}$)

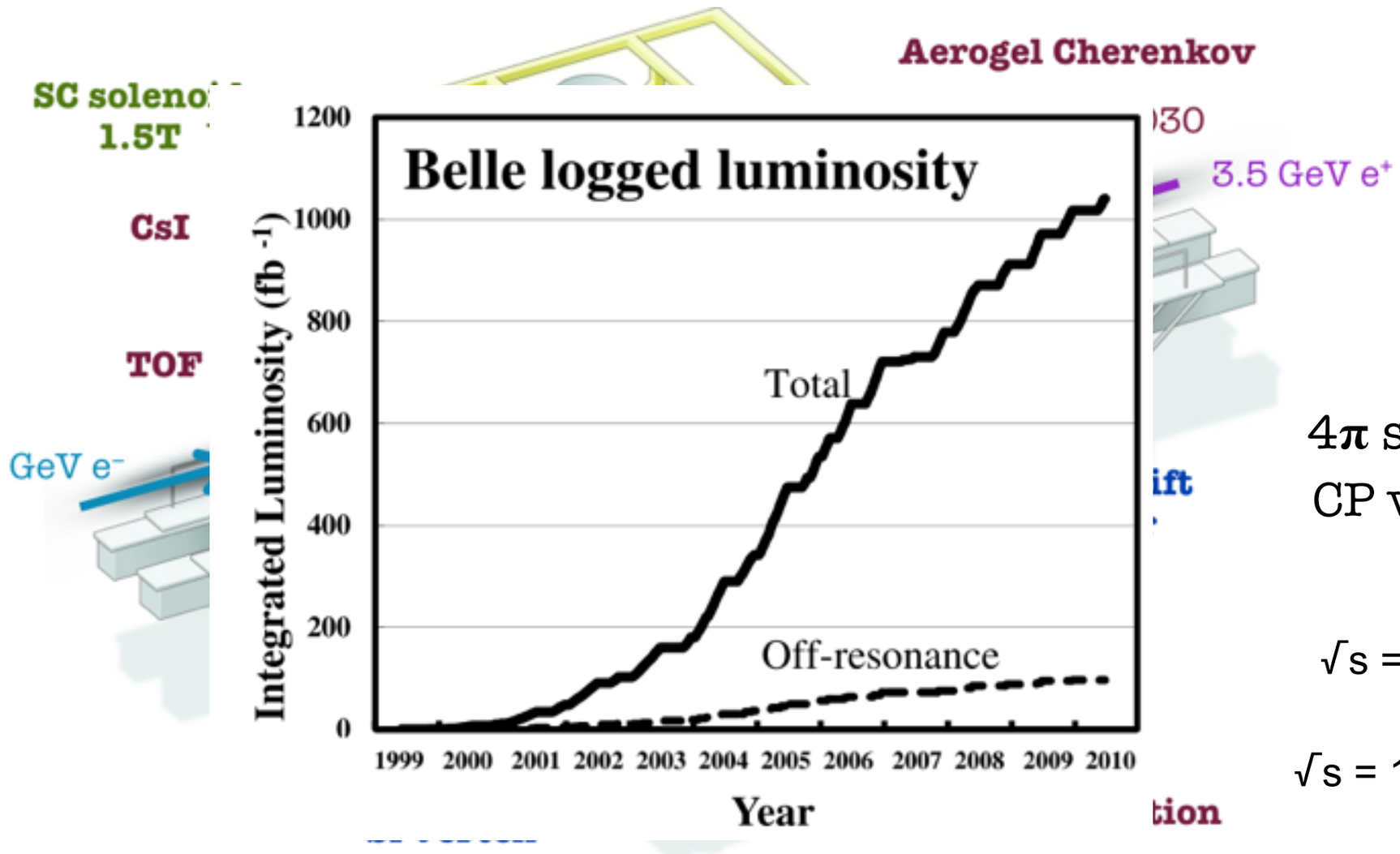
Off resonance
$\sqrt{s}$ = 10.52 GeV (e+ e- → $q\bar{q}$ (q=u,d,s,c))

Total Luminosity collected:
1000 $fb^{-1}$!!!

Good tracking $\Theta$ [$17^0$;$150^0$]
and vertex resolution

Good PID: $\varepsilon(\pi) \gtrsim 90\%$
$\varepsilon(K) \gtrsim 85\%$

# BELLE @ KEKB




KEKB:
Asymmetric e+ e- collider
(3.5 / 8 GeV)

Belle spectrometer:
$4\pi$ spectrometer optimized for
CP violation in B-meson decay

On resonance:
$\sqrt{s}$ = 10.58 GeV (e+ e- → $\Upsilon(4S) \to B\bar{B}$)

Off resonance
$\sqrt{s}$ = 10.52 GeV (e+ e- → $q\bar{q}$ (q=u,d,s,c))

Total Luminosity collected:
1000 fb$^{-1}$!!!

Good tracking $\Theta$ [17$^0$;150$^0$]
and vertex resolution

Good PID: $\varepsilon(\pi) \gtrsim 90\%$
$\varepsilon(K) \gtrsim 85\%$

# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

Perfect PID ⇨ $j = i$

# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

Perfect PID ⇨ $j = i$

**BUT!!**

ε(π) ≳ 90%  ε(K) ≳ 85%

# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

Perfect PID ⇨ $j = i$

**BUT!!**

ε(π) ≳ 90%  ε(K) ≳ 85%

$$\pi \xrightarrow{90\%} \pi$$

# Cross sections extraction

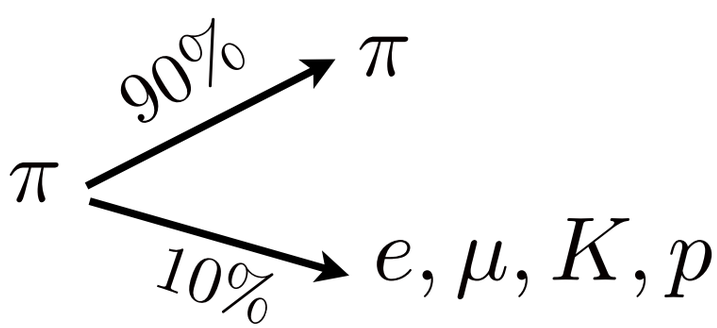
$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

Perfect PID ⇨ $j = i$

**BUT!!**

ε(π) ≳ 90%  ε(K) ≳ 85%



# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

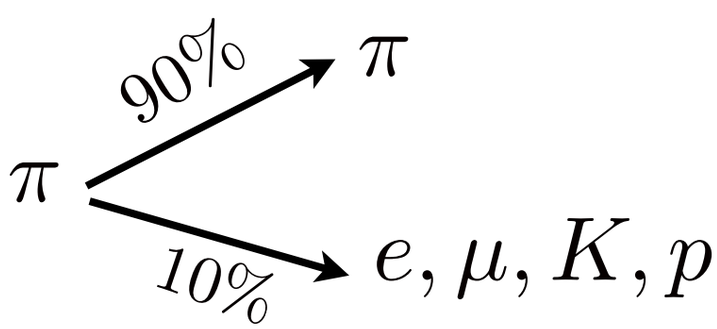
Perfect PID ⇨ $j = i$

$$N^{j,raw} = P_{ij} N^i$$

$j = e, \mu, \pi, K, p$

**BUT!!**

ε(π) ≳ 90%  ε(K) ≳ 85%




$$P_{ij} = \begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

# Cross sections extraction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

Perfect PID ⇨ $j = i$

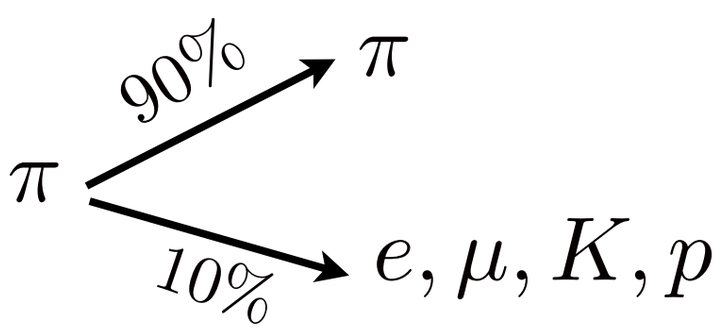
$j = e, \mu, \pi, K, p$

$$N^{j,raw} = P_{ij} N^i$$

$$N^i = P^{-1}_{ij} N^{j,raw}$$

**BUT!!**

ε(π) ≳ 90%  ε(K) ≳ 85%




$$P_{ij} = \begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

# How to determine the $P_{ij}$?

# How to determine the $P_{ij}$?

From data!

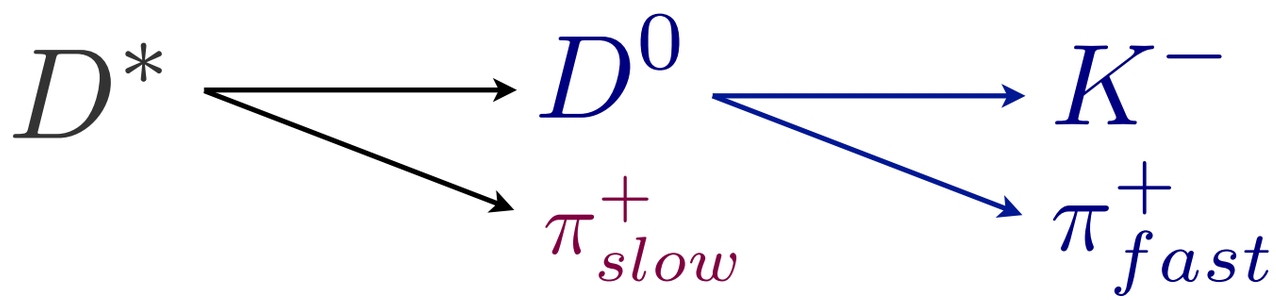
# How to determine the $P_{ij}$?

$$D^* \rightarrow D^0$$
$$D^* \rightarrow \pi^+_{slow}$$

From data!

# How to determine the $P_{ij}$?

From data!

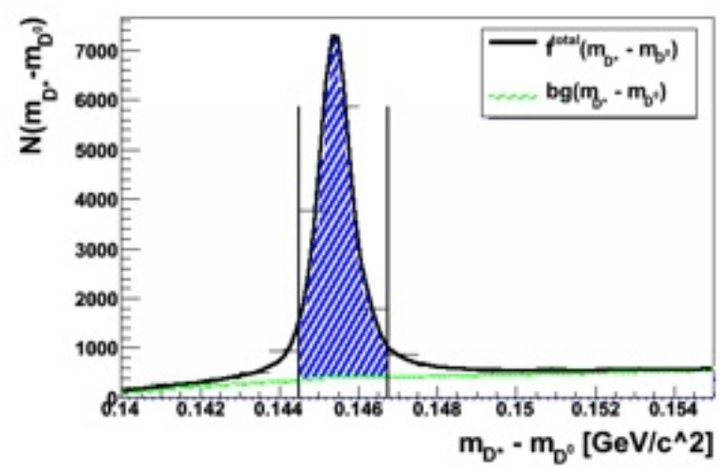


# How to determine the $P_{ij}$?

From data!

$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

$$m_D^* - m_D^0$$



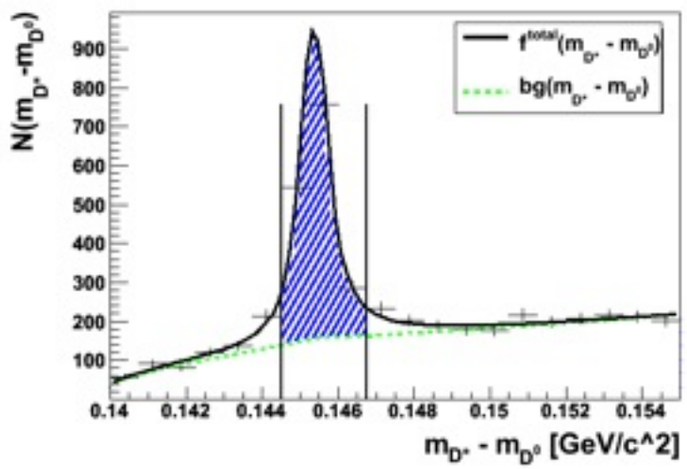

Negative hadron = $K^-$
(no PID likelihood used)

# How to determine the $P_{ij}$?

From data!

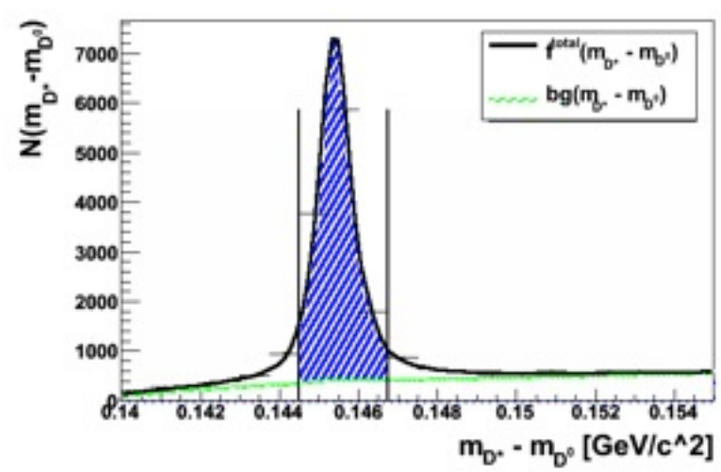
$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

$m_D^* - m_D^0$




Negative hadron identified as $\pi^-$

$m_D^* - m_D^0$



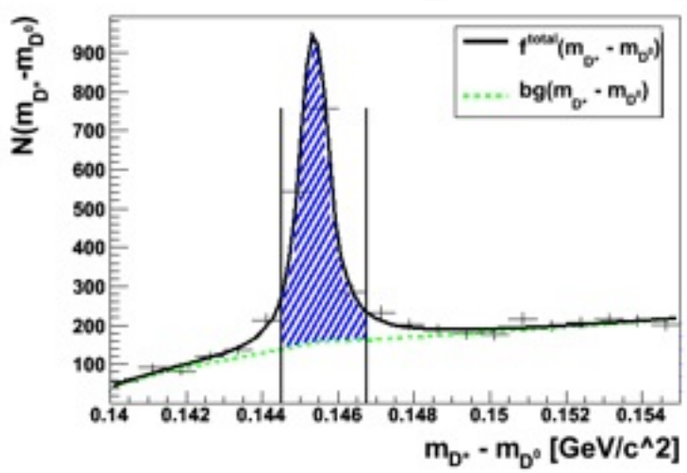

Negative hadron = $K^-$
(no PID likelihood used)

# How to determine the $P_{ij}$?

From data!

$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

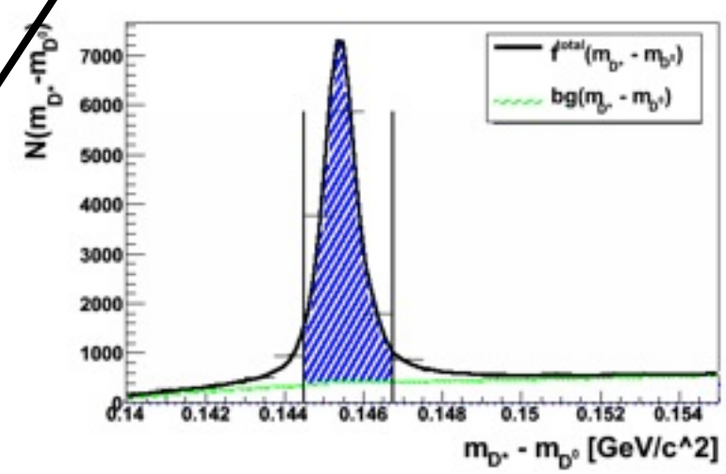
$m_D^* - m_D^0$




Negative hadron identified as $\pi^-$

$P_{K^- \to \pi^-}$

$m_D^* - m_D^0$



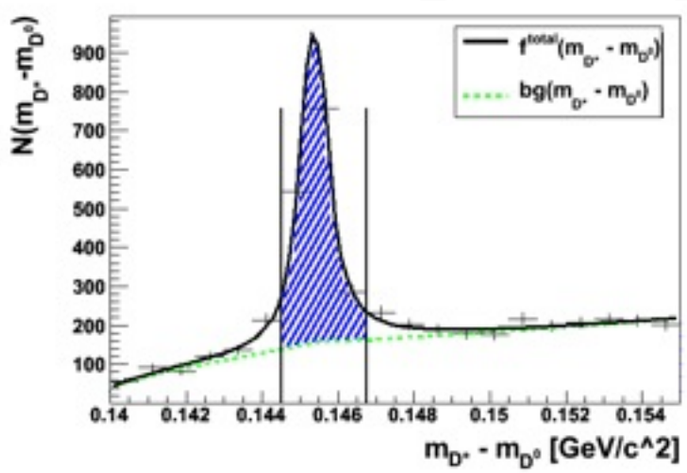

Negative hadron = $K^-$
(no PID likelihood used)

# How to determine the $P_{ij}$?

From data!

$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

$m_D^* - m_D^0$

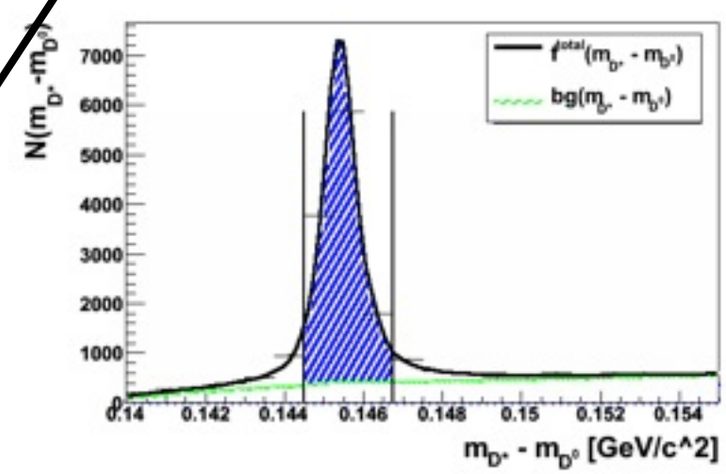



Negative hadron identified as $\pi^-$

$K^-$

$P_{K^- \to \pi^-}$

$m_D^* - m_D^0$




$P_{K^- \to K^-}$

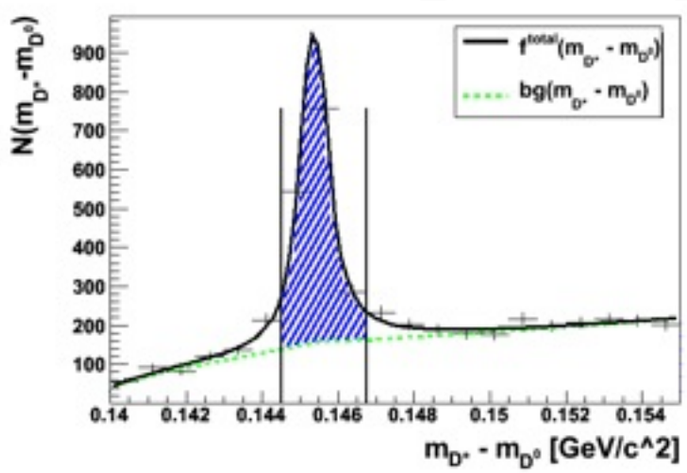
Negative hadron = $K^-$
(no PID likelihood used)

# How to determine the $P_{ij}$?

From data!

$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

$m_D^* - m_D^0$



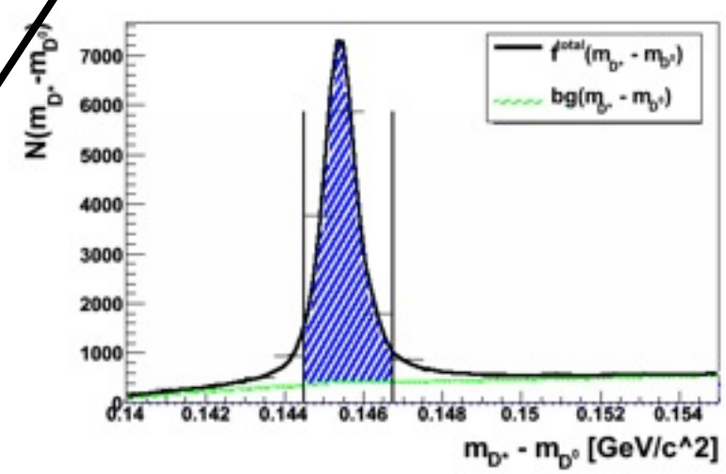

Negative hadron identified as $\pi^-$

$K^-$

$\bar{p}$

$P_{K^- \to \pi^-}$

$m_D^* - m_D^0$




$P_{K^- \to K^-}$

$P_{K^- \to \bar{p}}$

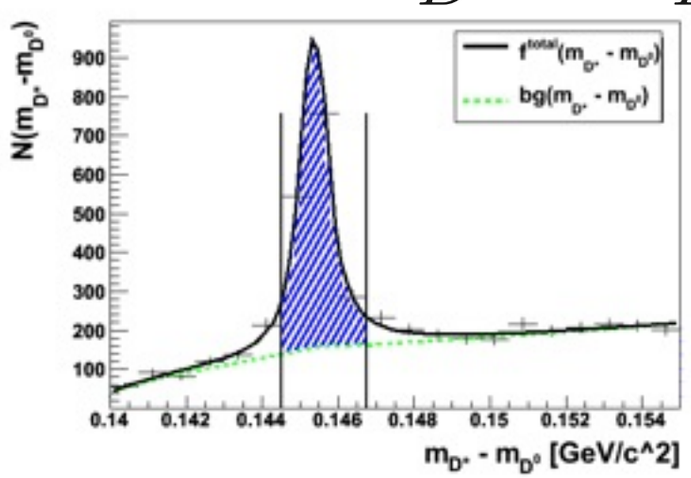
Negative hadron = $K^-$
(no PID likelihood used)

# How to determine the $P_{ij}$?

From data!

$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

$m_D^* - m_D^0$

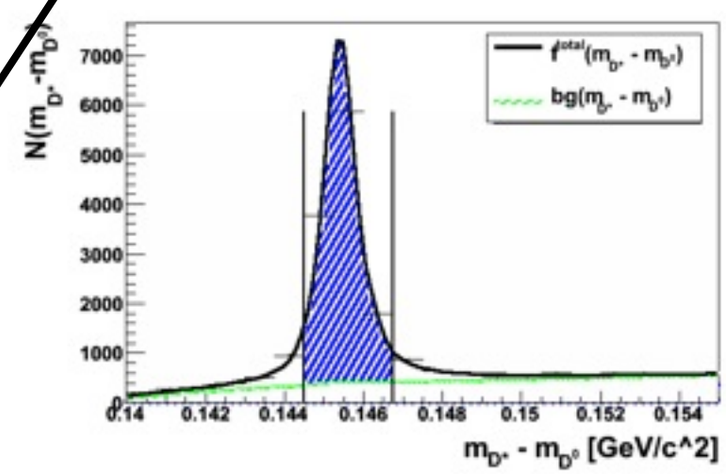



Negative hadron identified as $\pi^-$

$K^-$ $\bar{p}$ $\mu^-$

$P_{K^- \to \pi^-}$

$m_D^* - m_D^0$




Negative hadron = $K^-$
(no PID likelihood used)

$P_{K^- \to K^-}$

$P_{K^- \to \bar{p}}$

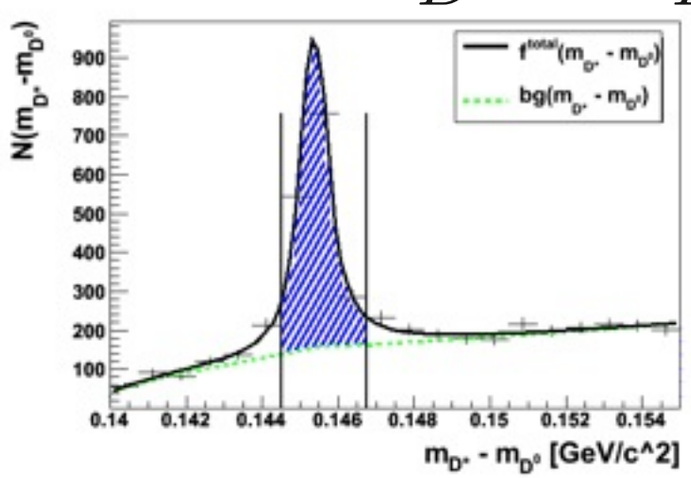
$P_{K^- \to \mu^-}$

# How to determine the $P_{ij}$?

From data!

$$D^* \to D^0 + \pi^+_{slow}, \quad D^0 \to K^- + \pi^+_{fast}$$

$m_D^* - m_D^0$

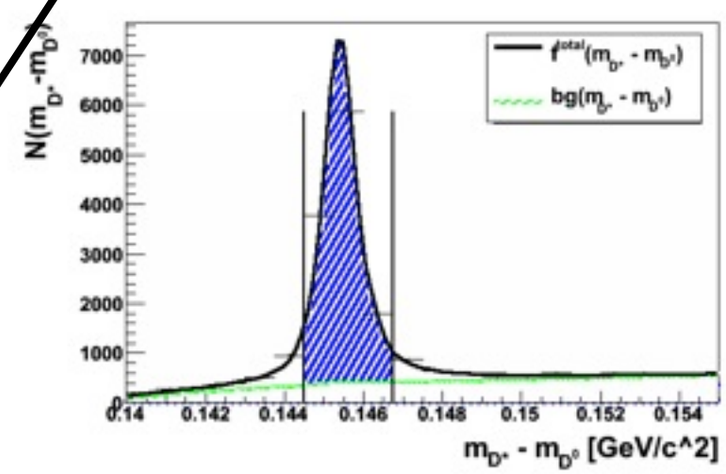



Negative hadron identified as $\pi^-$

$K^-$ $\bar{p}$ $\mu^-$ $e^-$

$P_{K^- \to \pi^-}$

$m_D^* - m_D^0$




Negative hadron = $K^-$
(no PID likelihood used)

$P_{K^- \to K^-}$
$P_{K^- \to \bar{p}}$
$P_{K^- \to \mu^-}$
$P_{K^- \to e^-}$

# 2D correction

Detector performance depends on momentum and scattering angle!

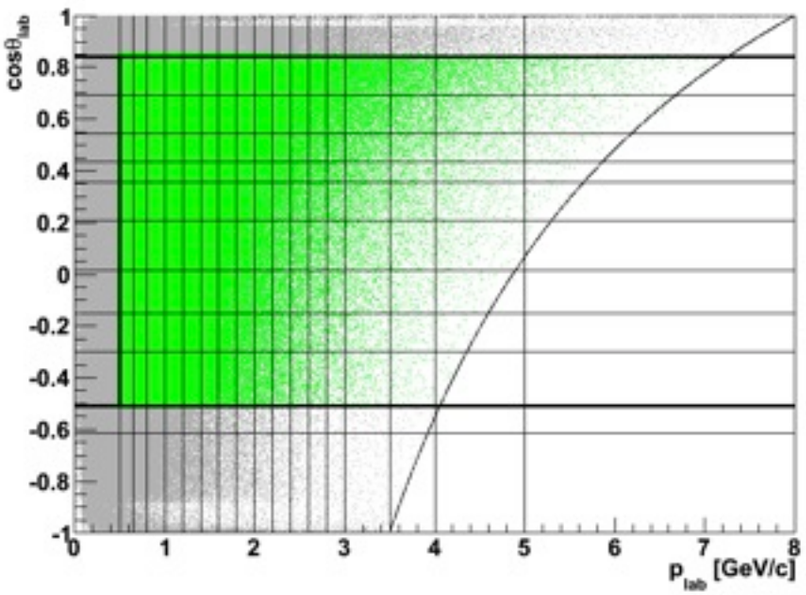
# 2D correction

Detector performance depends on momentum
and scattering angle!

$$P_{ij} \Rightarrow P_{ij}(p, \theta)$$

# 2D correction

Detector performance depends on momentum and scattering angle!

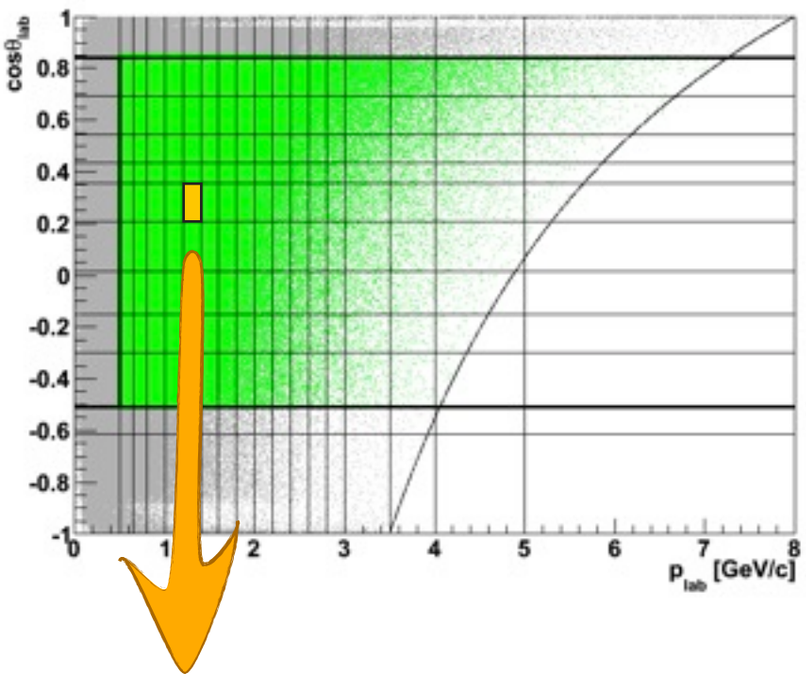



$$P_{ij} \Rightarrow P_{ij}(p, \theta)$$

| Bin # | $\cos\theta_{lab}$ bin ranges |
|---|---|
| 0 | [-0.511,-0.300) |
| 1 | [-0.300,-0.152) |
| 2 | [-0.512,0.017) |
| 3 | [0.017,0.209) |
| 4 | [0.209,0.355) |
| 5 | [0.355,0.435) |
| 6 | [0.435,0.542) |
| 7 | [0.542,0.692) |
| 8 | [0.692,0.842) |

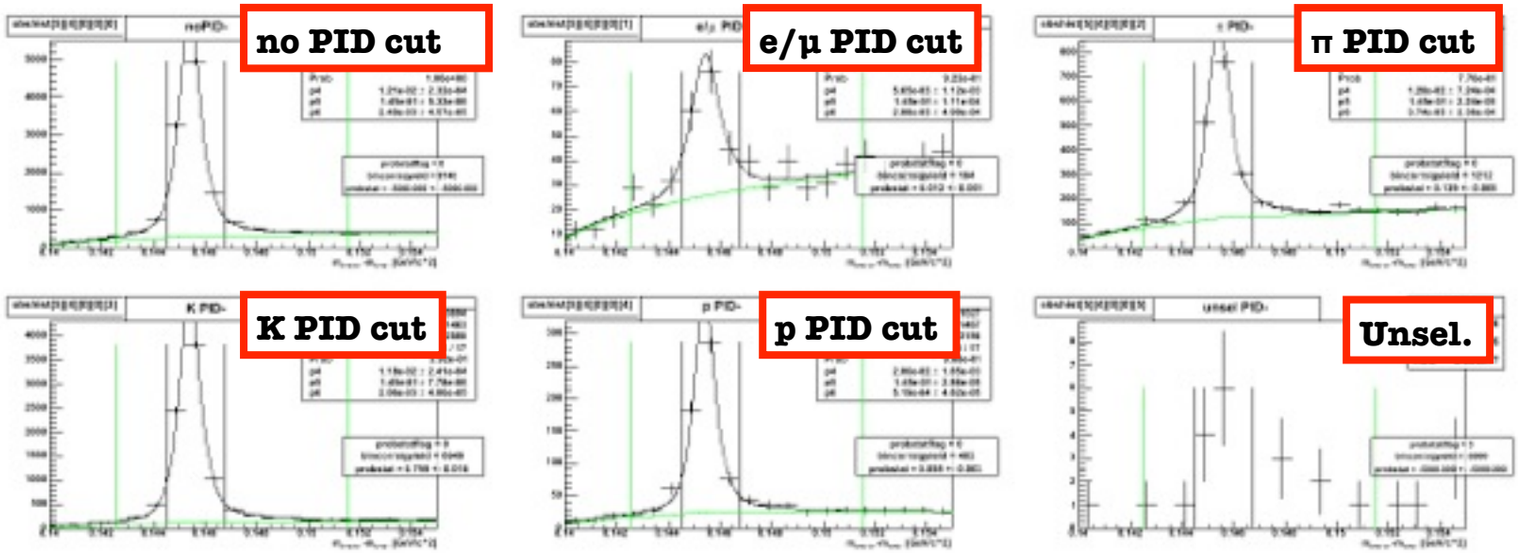
| Bin # | $p_{lab}$ [GeV/c] bin ranges |
|---|---|
| 0 | [0.5,0.65) |
| 1 | [0.65,0.8) |
| 2 | [0.8,1.0) |
| 3 | [1.0,1.2) |
| 4 | [1.2,1.4) |
| 5 | [1.4,1.6) |
| 6 | [1.6,1.8) |
| 7 | [1.8,2.0) |
| 8 | [2.0,2.2) |
| 9 | [2.2,2.4) |
| 10 | [2.4,2.6) |
| 11 | [2.6,2.8) |
| 12 | [2.8,3.0) |
| 13 | [3.0,3.5) |
| 14 | [3.5,4.0) |
| 15 | [4.0,5.0) |
| 16 | [5.0,8.0) |

# 2D correction

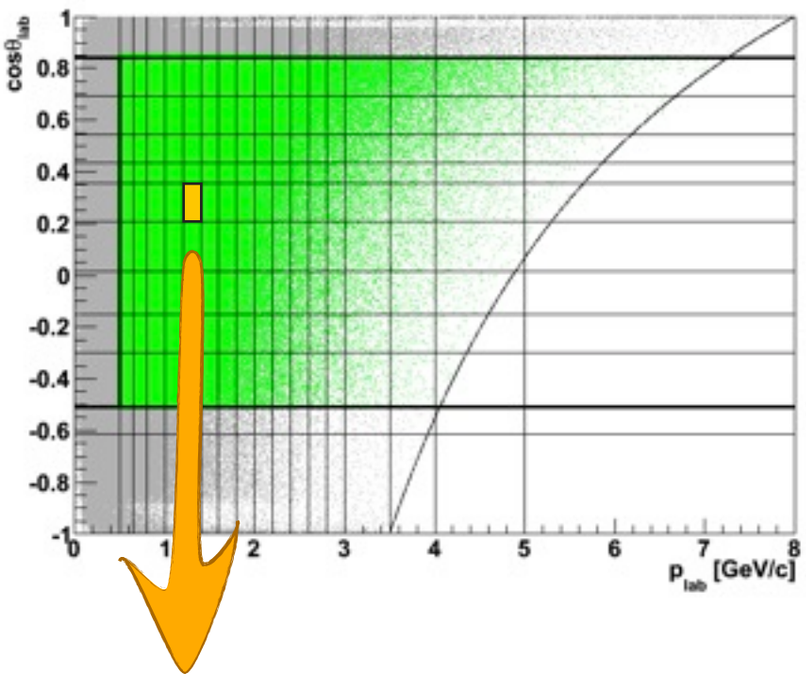



$$\begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

K from D* decay for $p_{lab}$ in [1.4,1.6) and $\cos\theta_{lab}$ in [0.209,0.355)

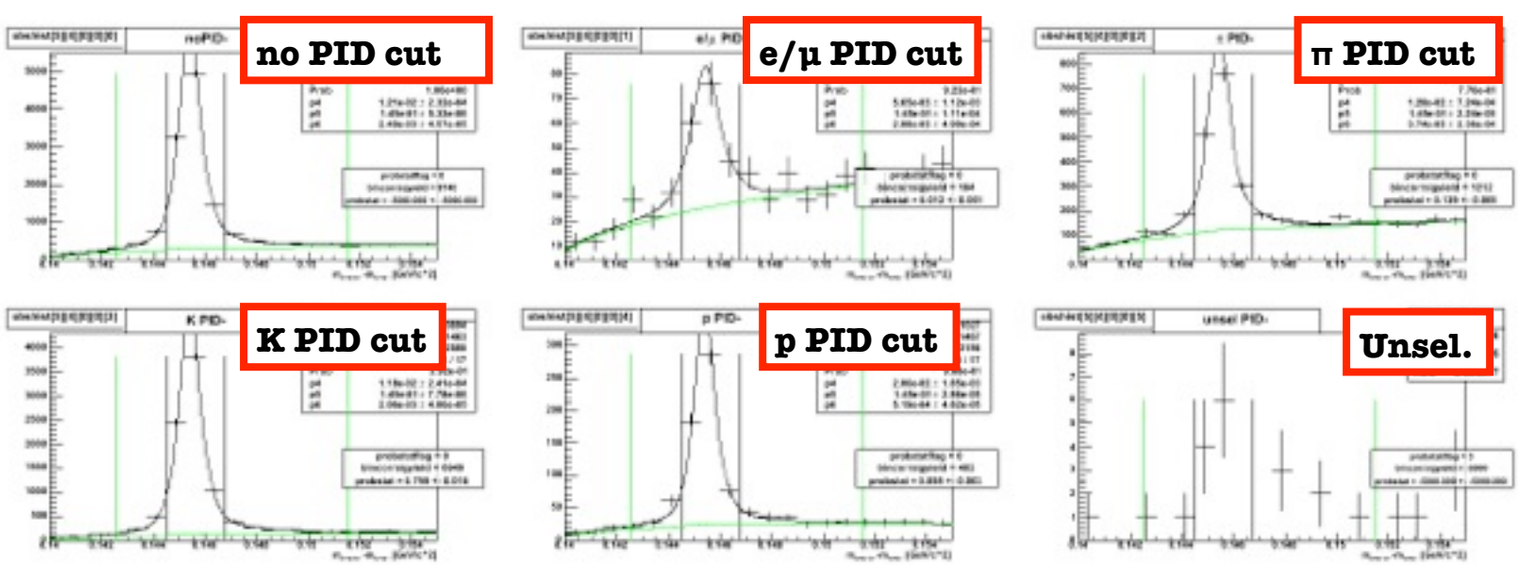


# 2D correction

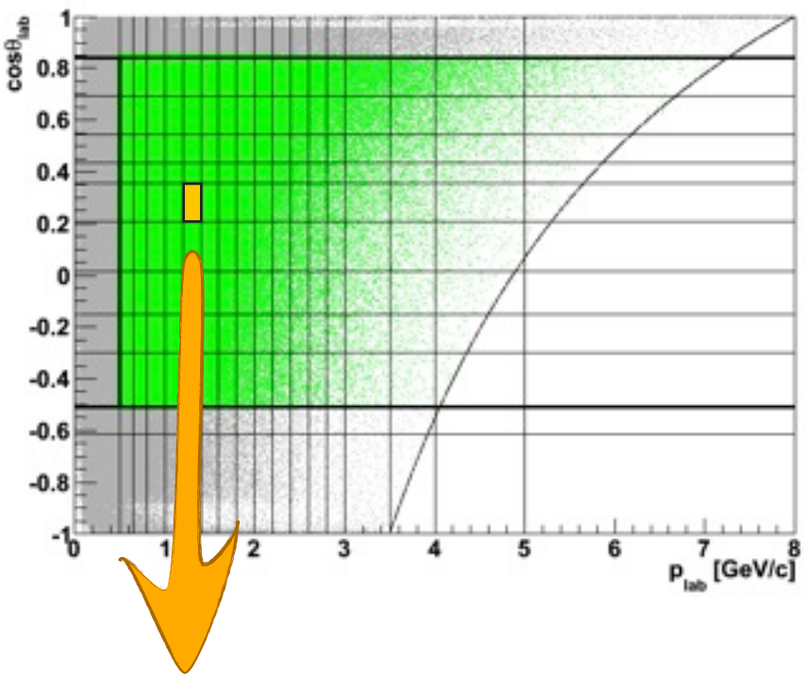



$$\begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

K from D* decay for $p_{lab}$ in [1.4,1.6) and $\cos\theta_{lab}$ in [0.209,0.355)



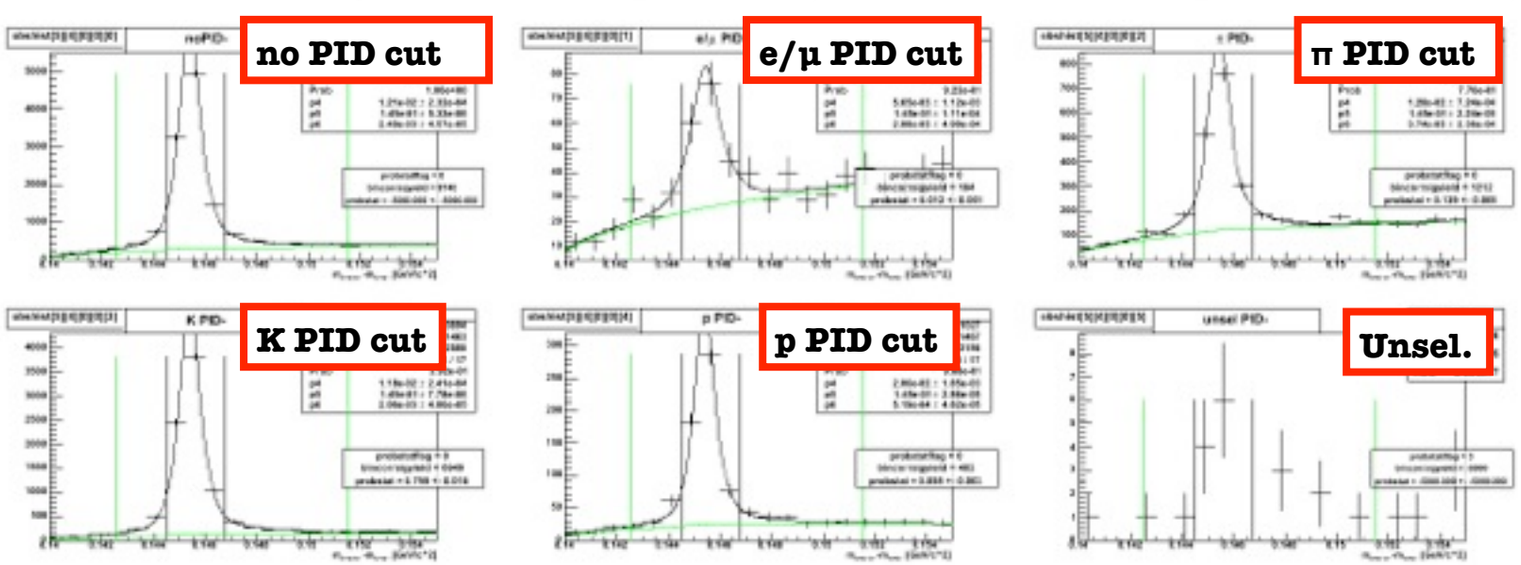
# 2D correction




$\mathbf{p}_{\pi,\,K\,\to\,j}$ from D* decay
$\mathbf{p}_{\pi,\,p\,\to\,j}$ from Λ decay
$\mathbf{p}_{e,\,\mu\,\to\,j}$ from J/ψ decay

$$\begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

K from D* decay for $p_{lab}$ in [1.4,1.6) and $\cos\theta_{lab}$ in [0.209,0.355)



# 2D correction

$$\begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

$\mathbf{p_{\pi,\,K\,\to\,j}}$ from D* decay

$\mathbf{p_{\pi,\,p\,\to\,j}}$ from Λ decay

$\mathbf{p_{e,\,\mu\,\to\,j}}$ from J/ψ decay

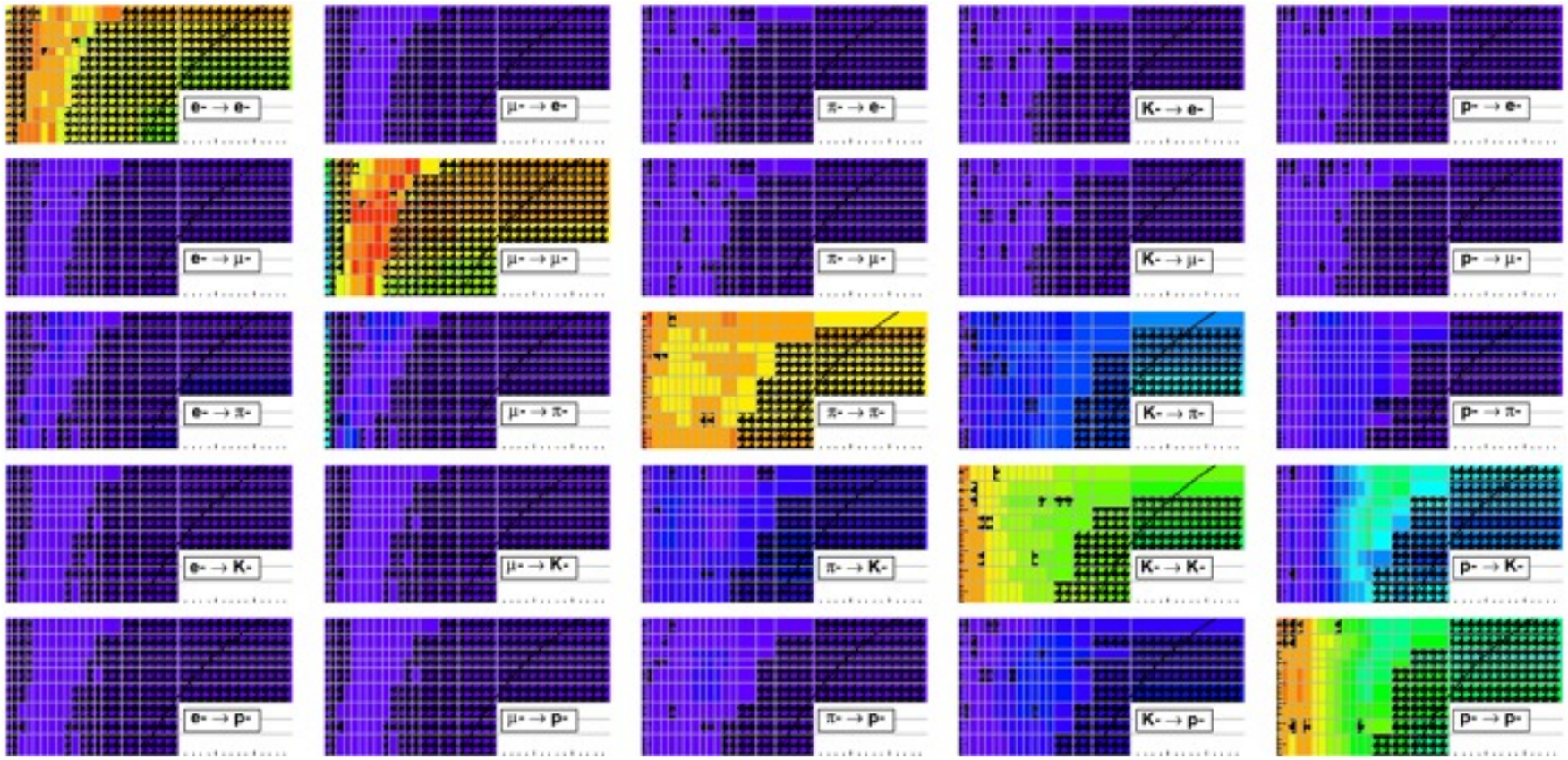
# 2D correction

$$\begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

$\mathbf{p}_{\pi,\,K\,\to\,j}$ from D* decay

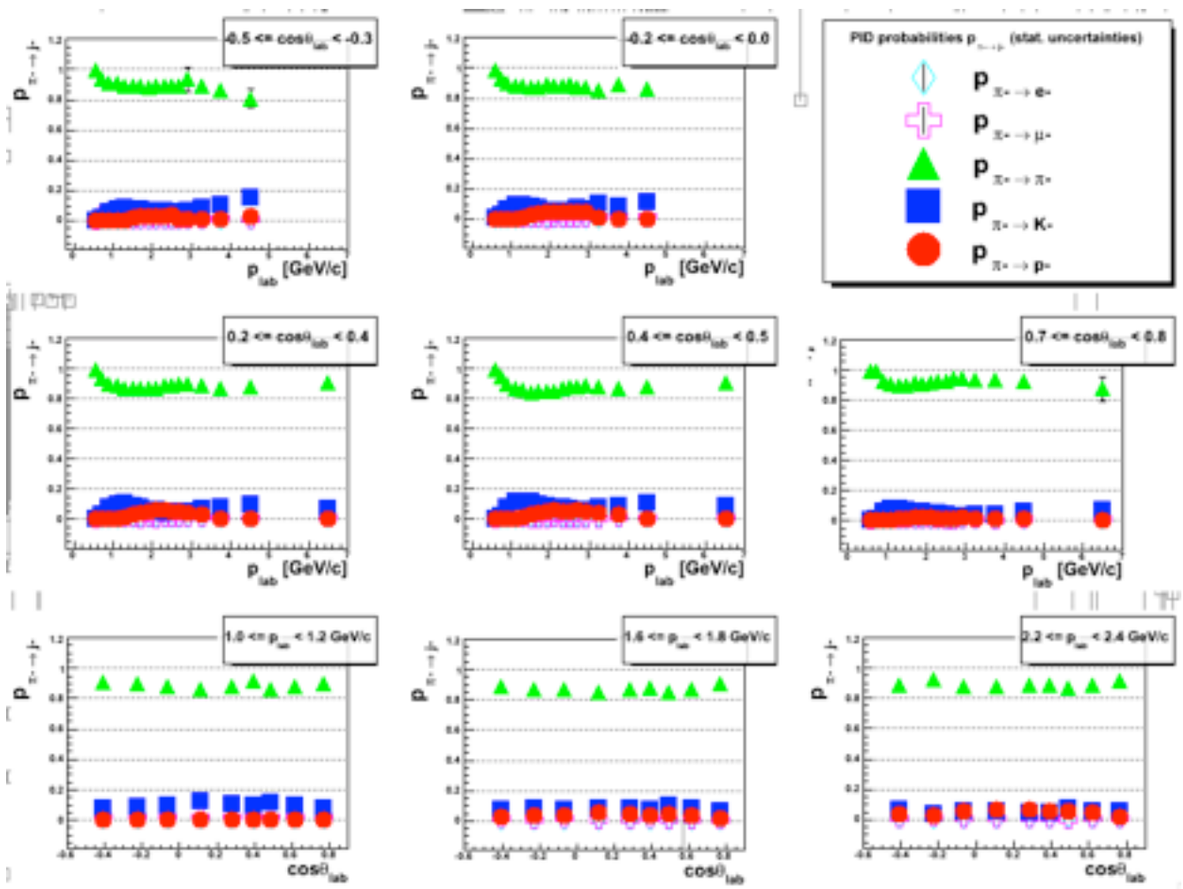
$\mathbf{p}_{\pi,\,p\,\to\,j}$ from Λ decay

$\mathbf{p}_{e,\,\mu\,\to\,j}$ from J/ψ decay



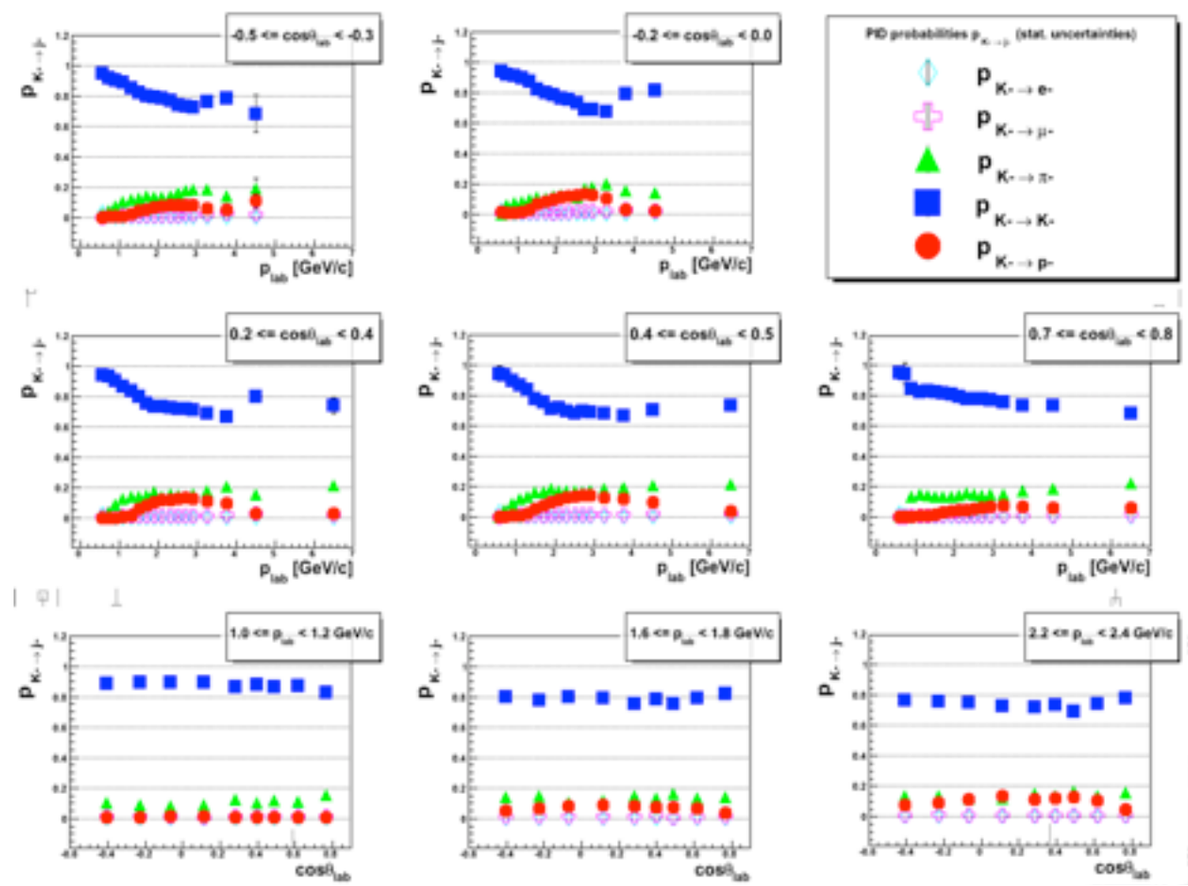
# PID correction

$\pi^-$




< 15%

$K^-$



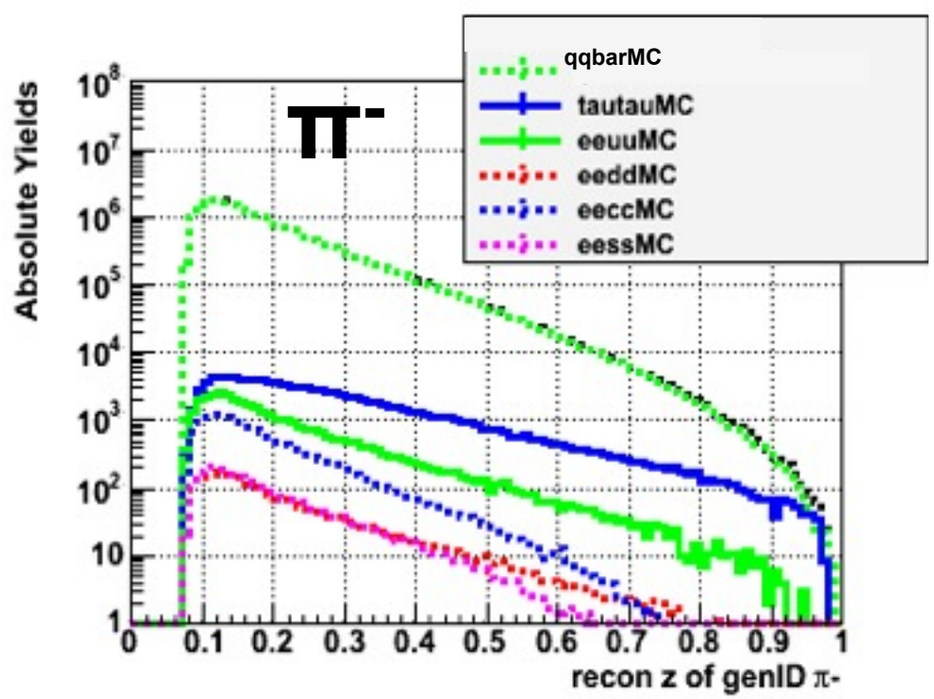

30% >

# Impurity correction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Correction for hadrons generated by ττ, 2γ

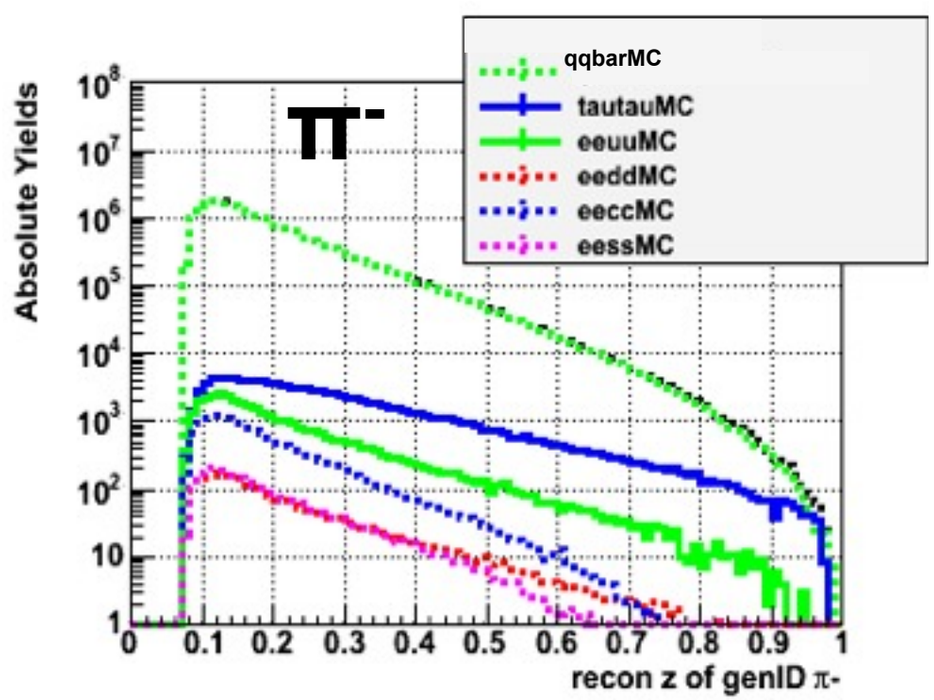


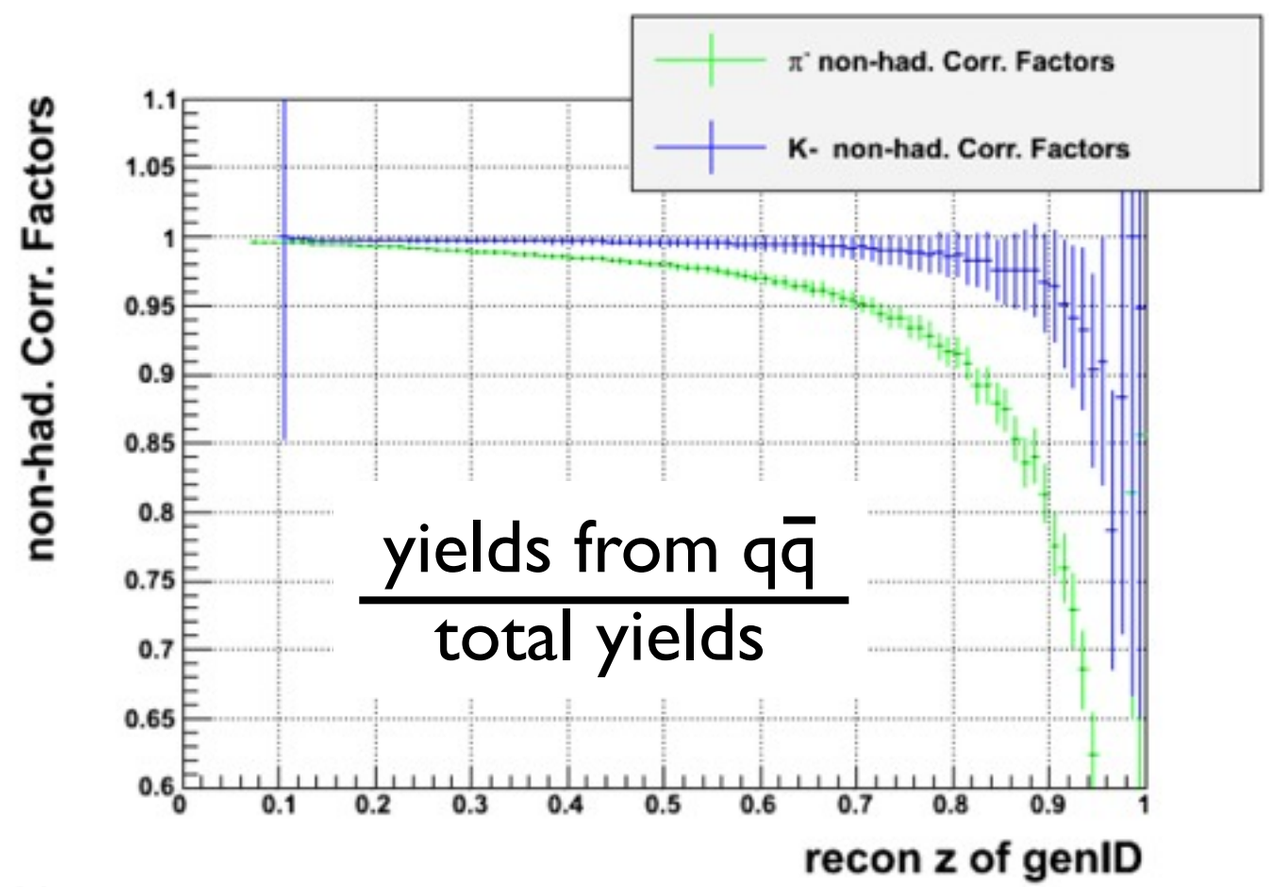
# Impurity correction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Correction for hadrons generated by ττ, 2γ



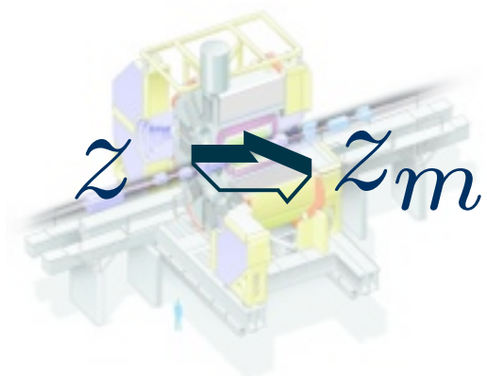



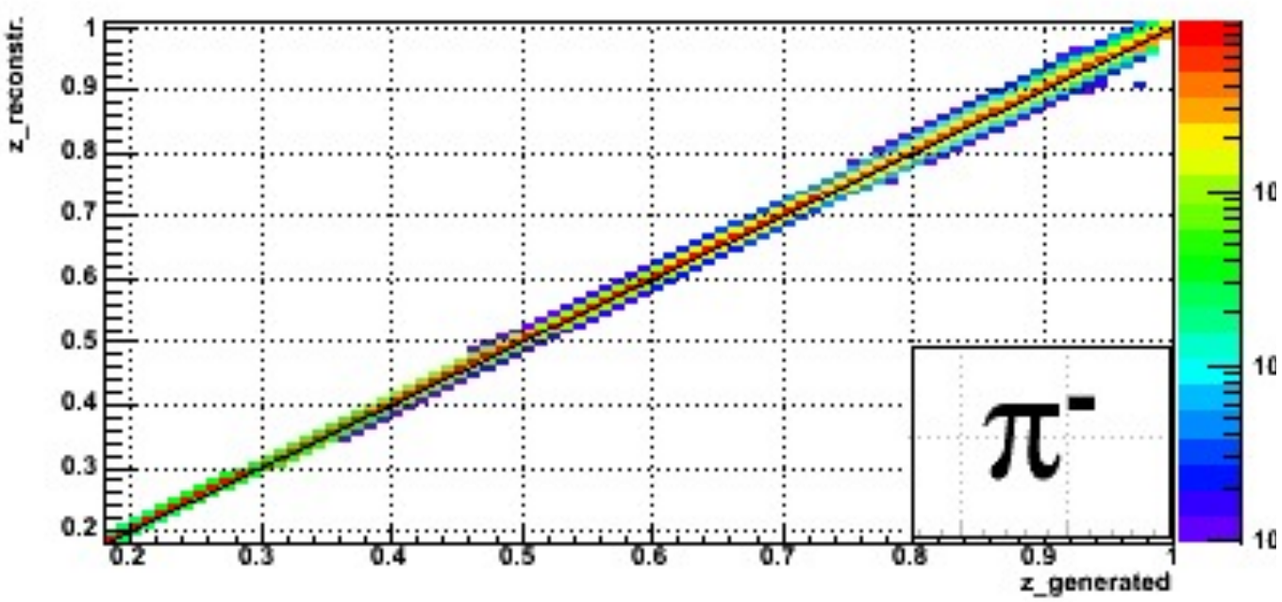
# Smearing correction

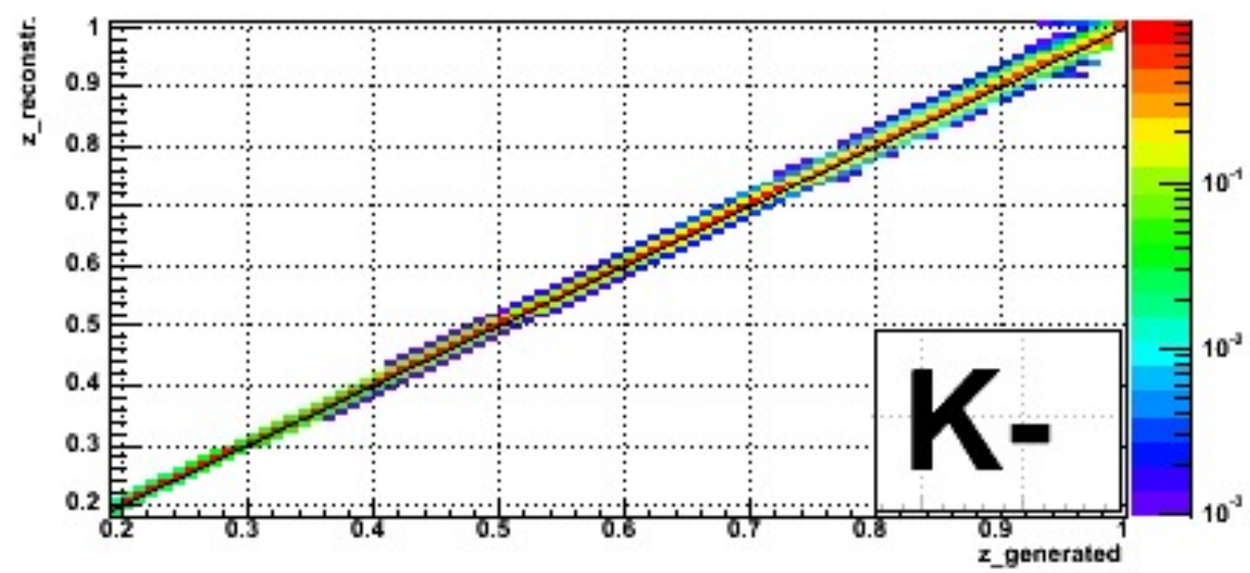
$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{z z_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Detector smearing correction



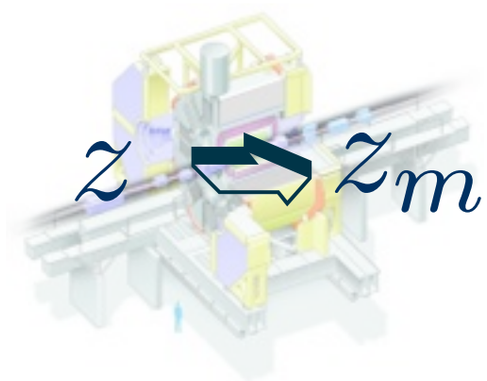



# Smearing correction

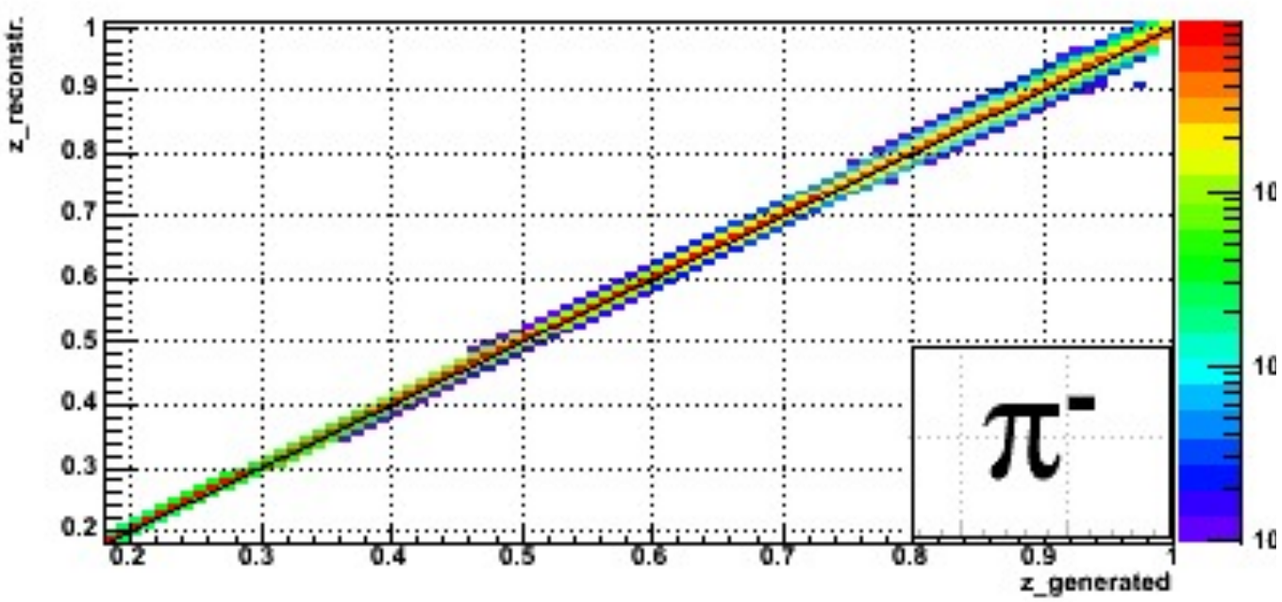
$i = \pi, K$

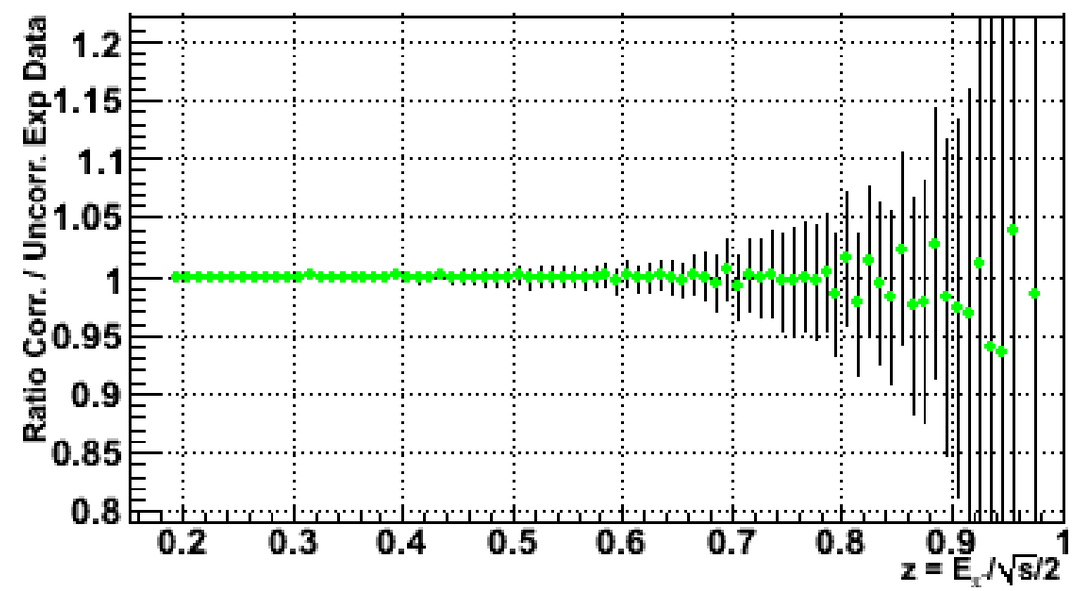
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{z z_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Detector smearing correction




before/after



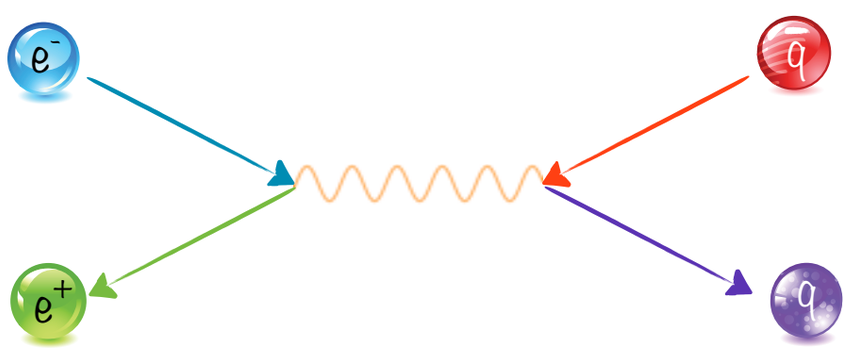



# ISR/FSR correction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Emission of a real photon changes the fragmentation energy scale

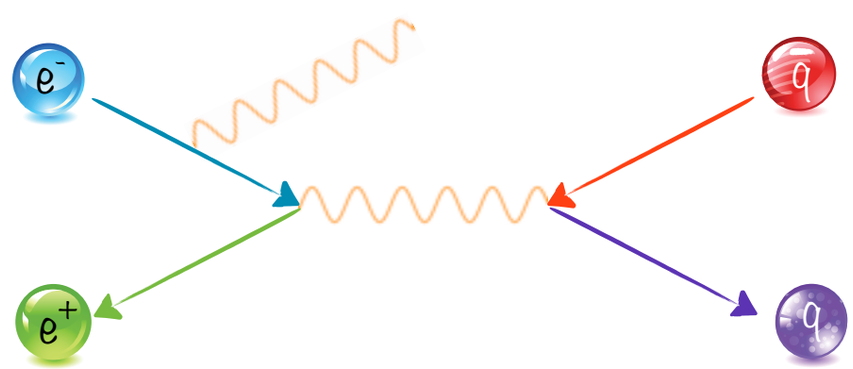


# ISR/FSR correction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Emission of a real photon changes the fragmentation energy scale

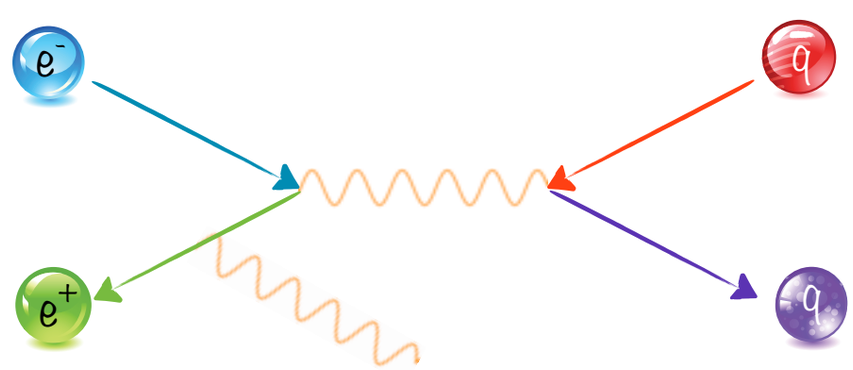


# ISR/FSR correction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Emission of a real photon changes the fragmentation energy scale

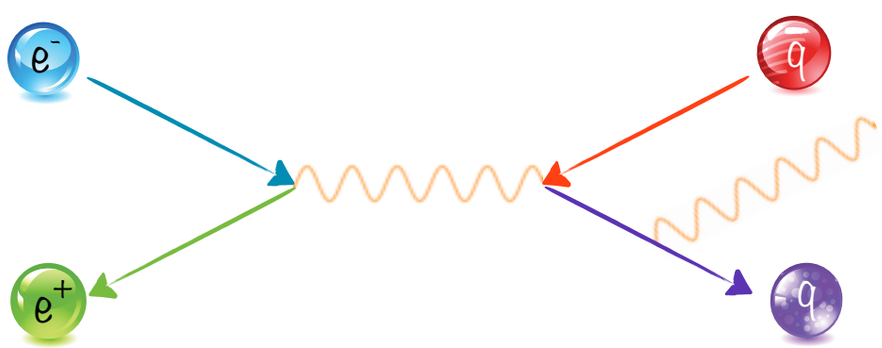


# ISR/FSR correction

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Emission of a real photon changes the fragmentation energy scale

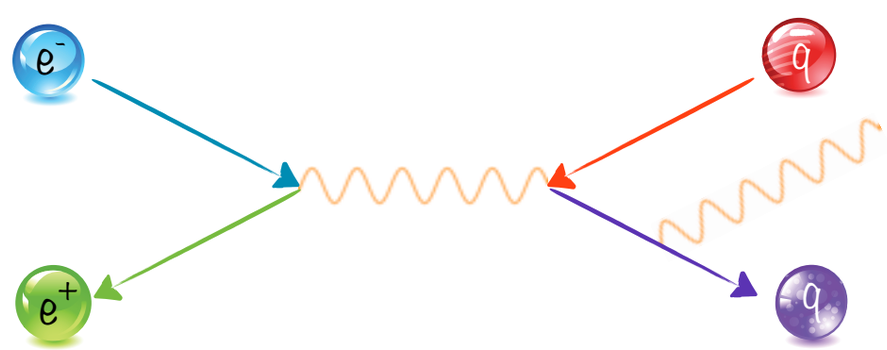


# ISR/FSR correction

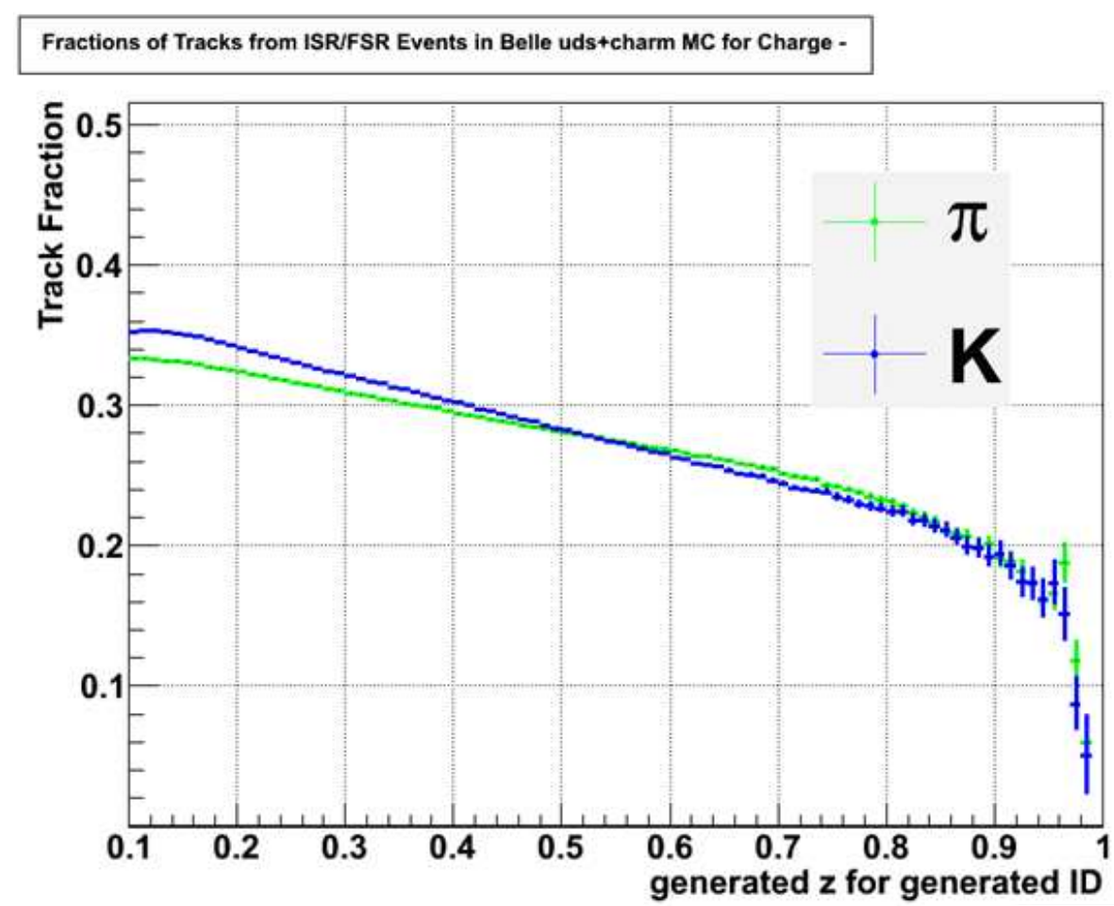
$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Emission of a real photon changes the fragmentation energy scale




> 0.5% change in cms energy

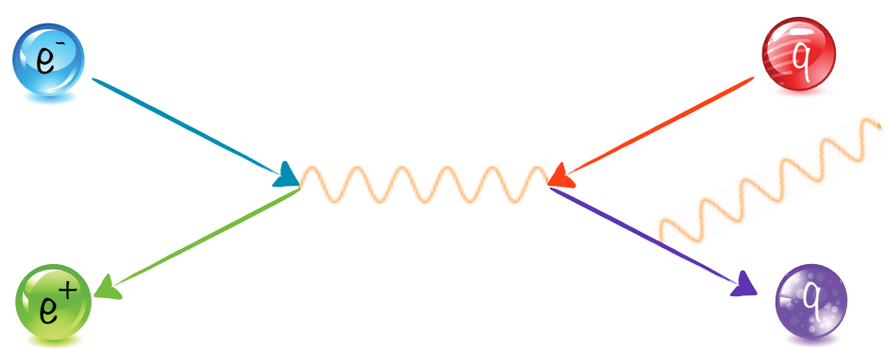


# ISR/FSR correction

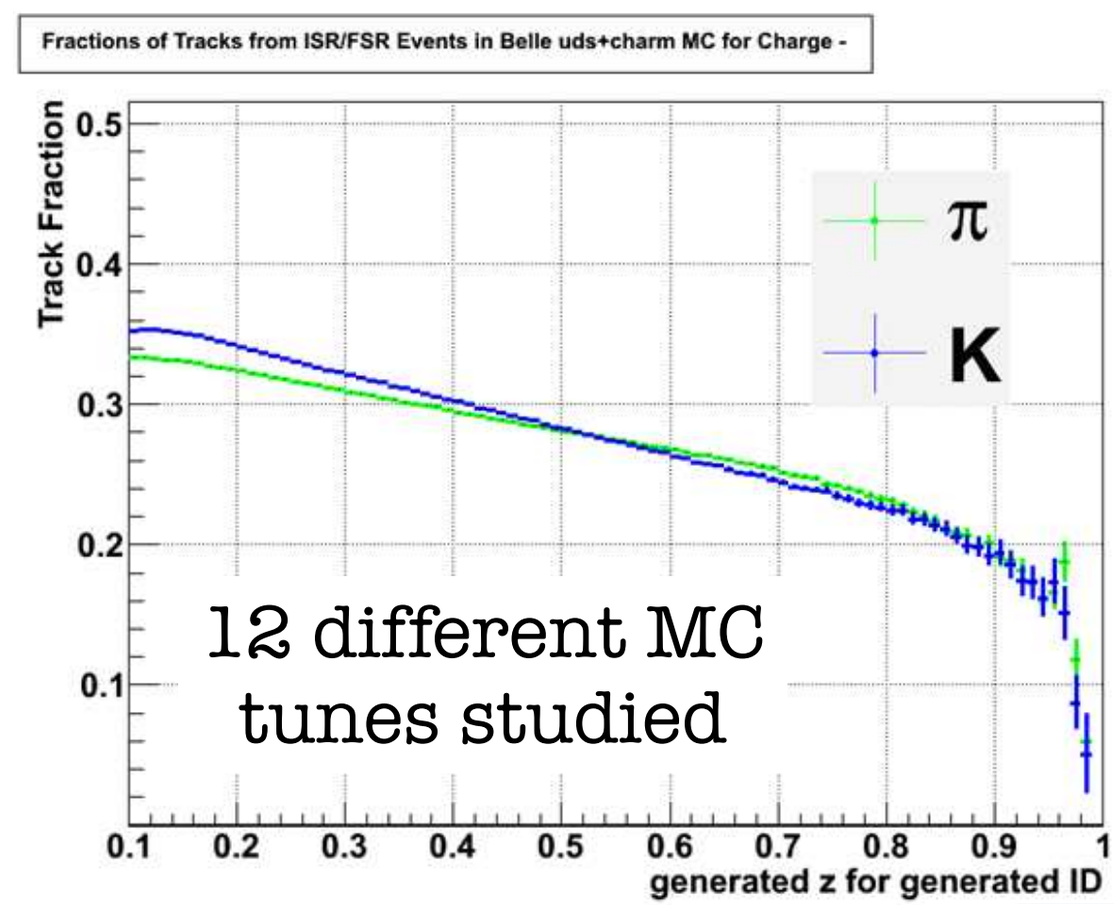
$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Emission of a real photon changes the fragmentation energy scale




> 0.5% change in cms energy



# More corrections

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \; \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Correction for particles lost due to

- decay in flight
- interaction with detectors
- detector/tracking inefficiencies
- geometric/kinematic acceptance

# More corrections

$i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \; \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

Correction for particles lost due to

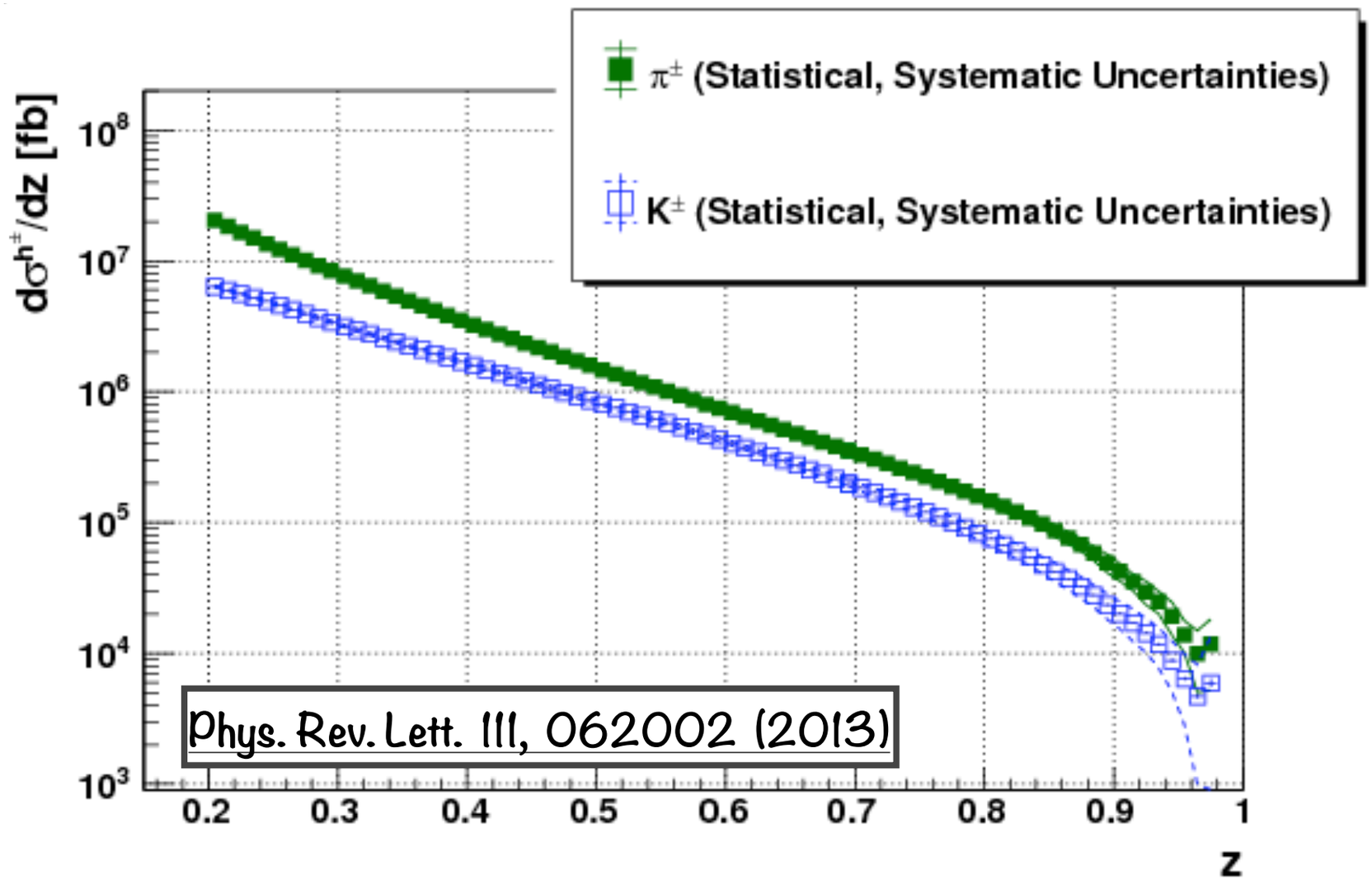
- decay in flight
- interaction with detectors
- detector/tracking inefficiencies
- geometric/kinematic acceptance

$\xi < 10\%$

# Cross sections

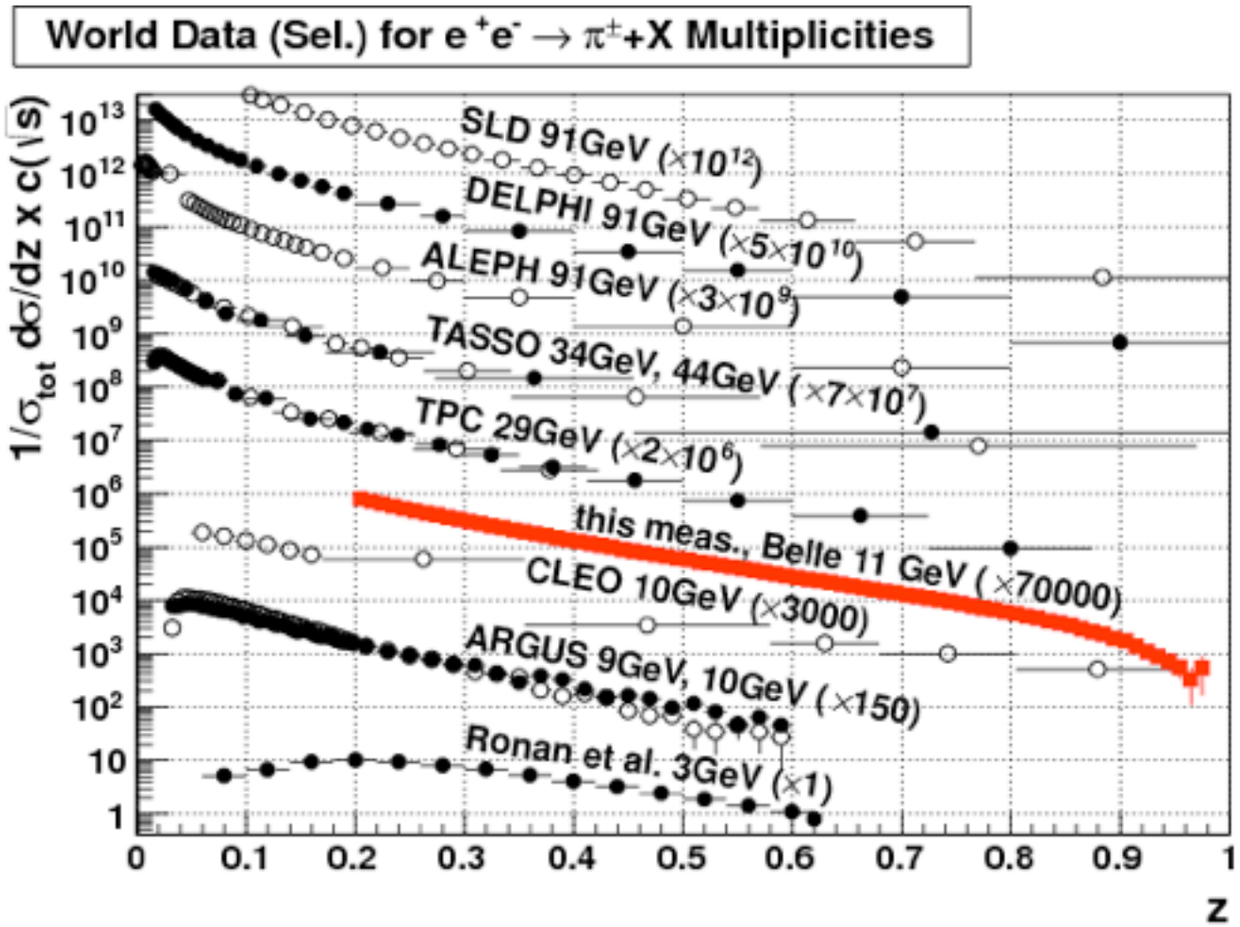
$i = \pi, K$

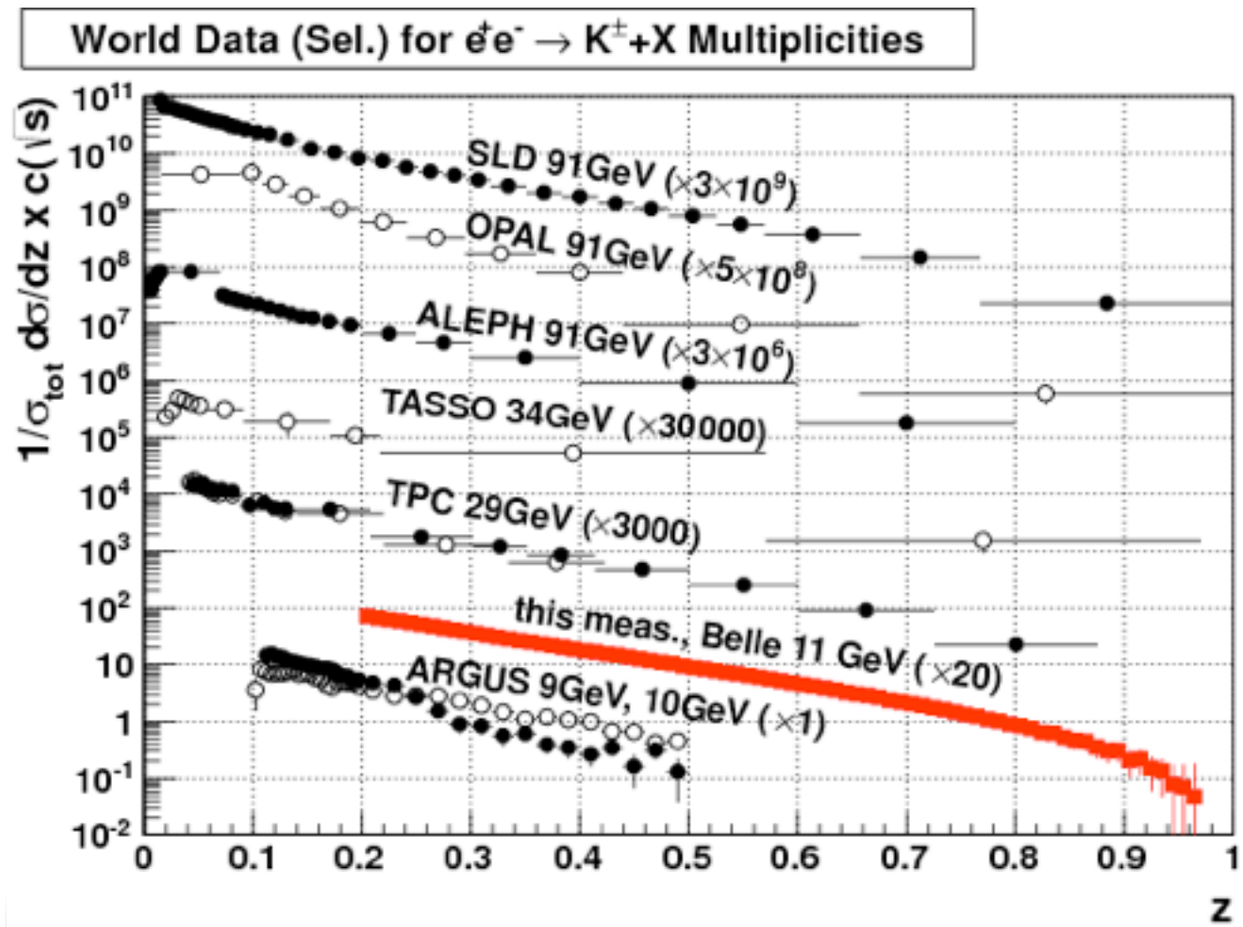
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \; \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$



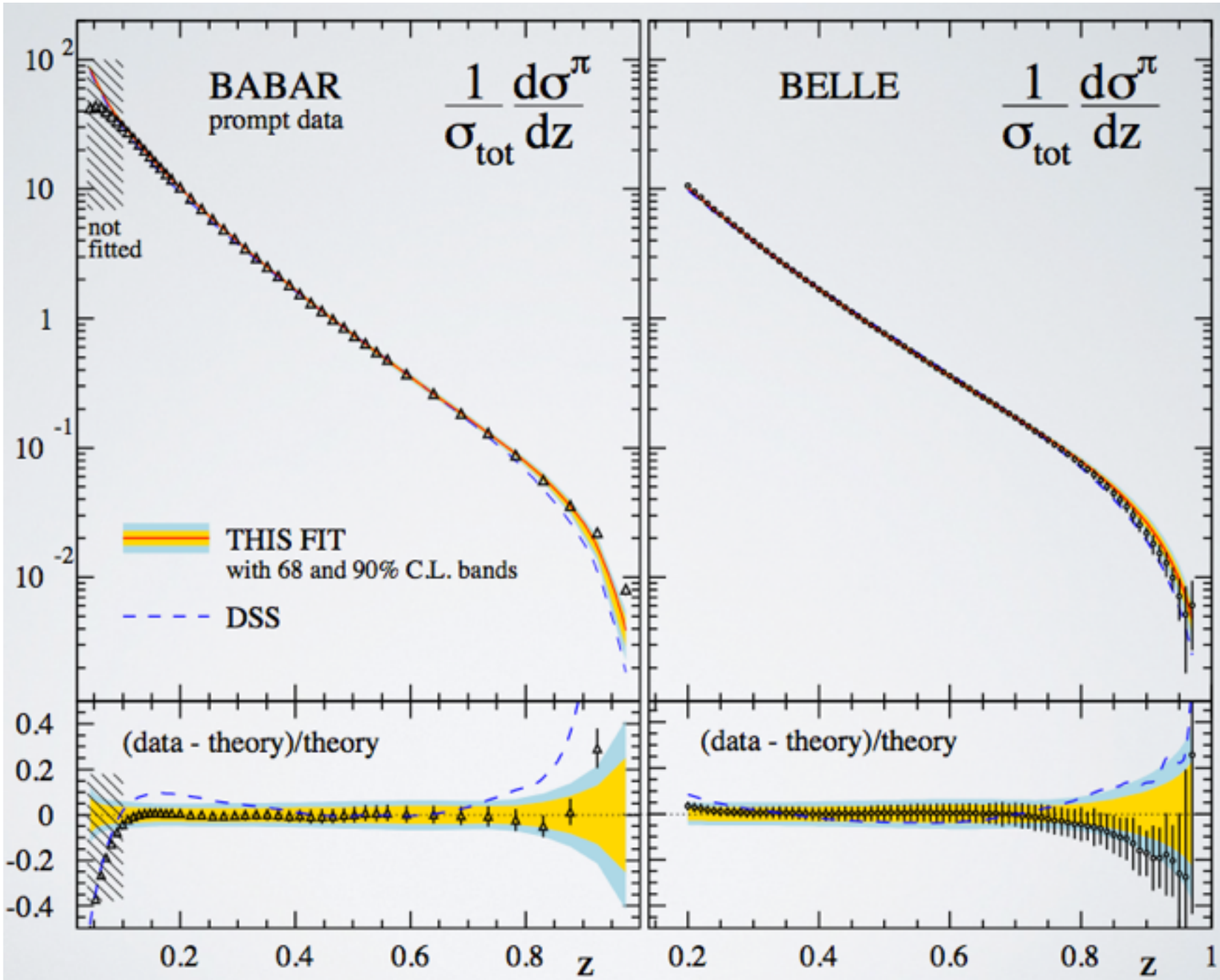

Phys. Rev. Lett. 111, 062002 (2013)

# Updated e+e- world data




Phys. Rev. Lett. 111, 062002 (2013)

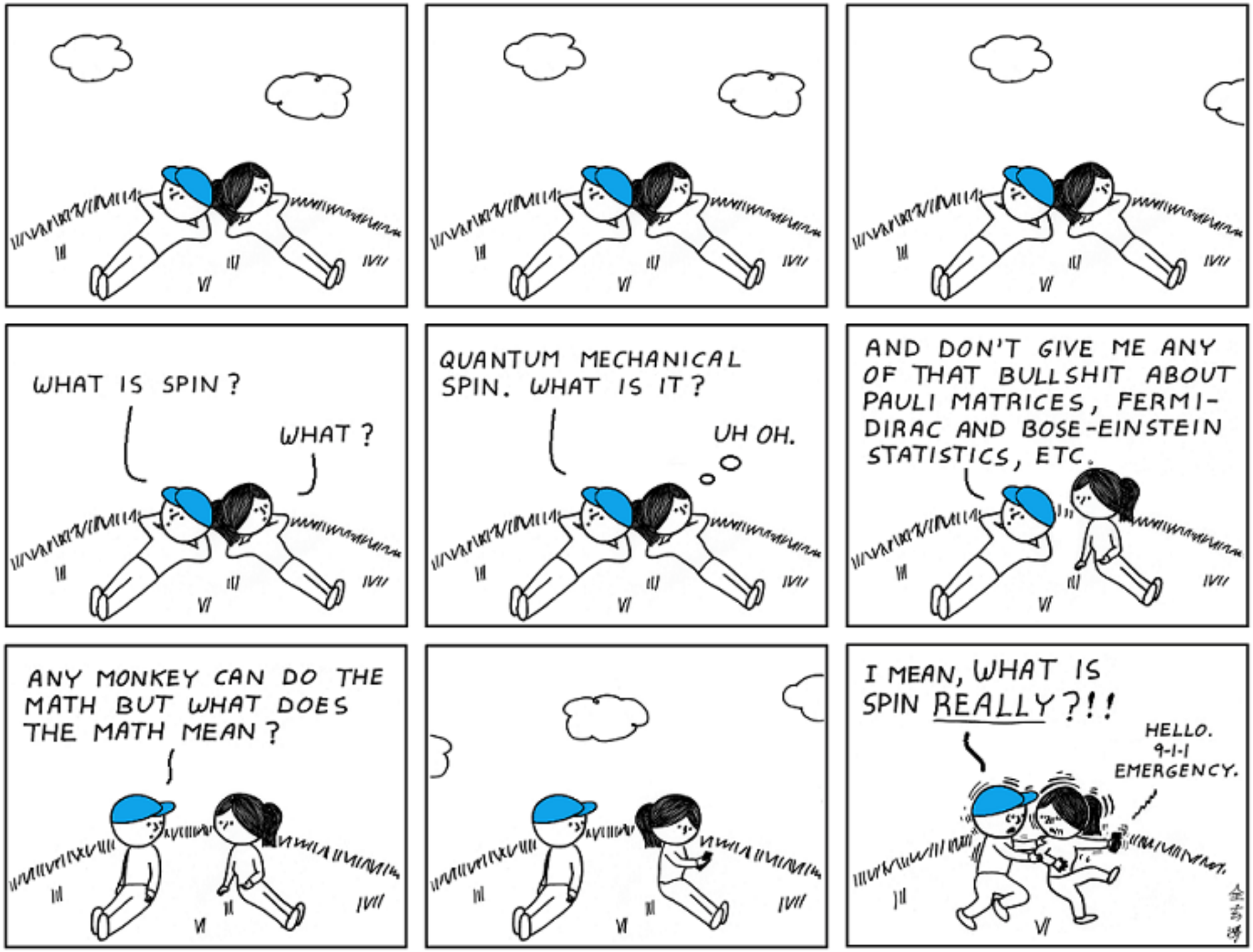



From Sassot slides last week...

Overall normalization factors needed to obtain consistent fit !

$N_{Belle}=1.058$, $N_{BarBar}=1.021$

# Moment of Clarity(?) - part 2




**I ask myself this question at least once a month.**



http://abstrusegoose.com/342