Precision boson-jet azimuthal decorrelation at hadron colliders

Yang-Ting Chien

Jet Physics: from RHIC/LHC to EIC, CFNS
June 30th, 2022

Phys. Lett. B 815 (2021) 136124 (2005.12279), and 2205.05104

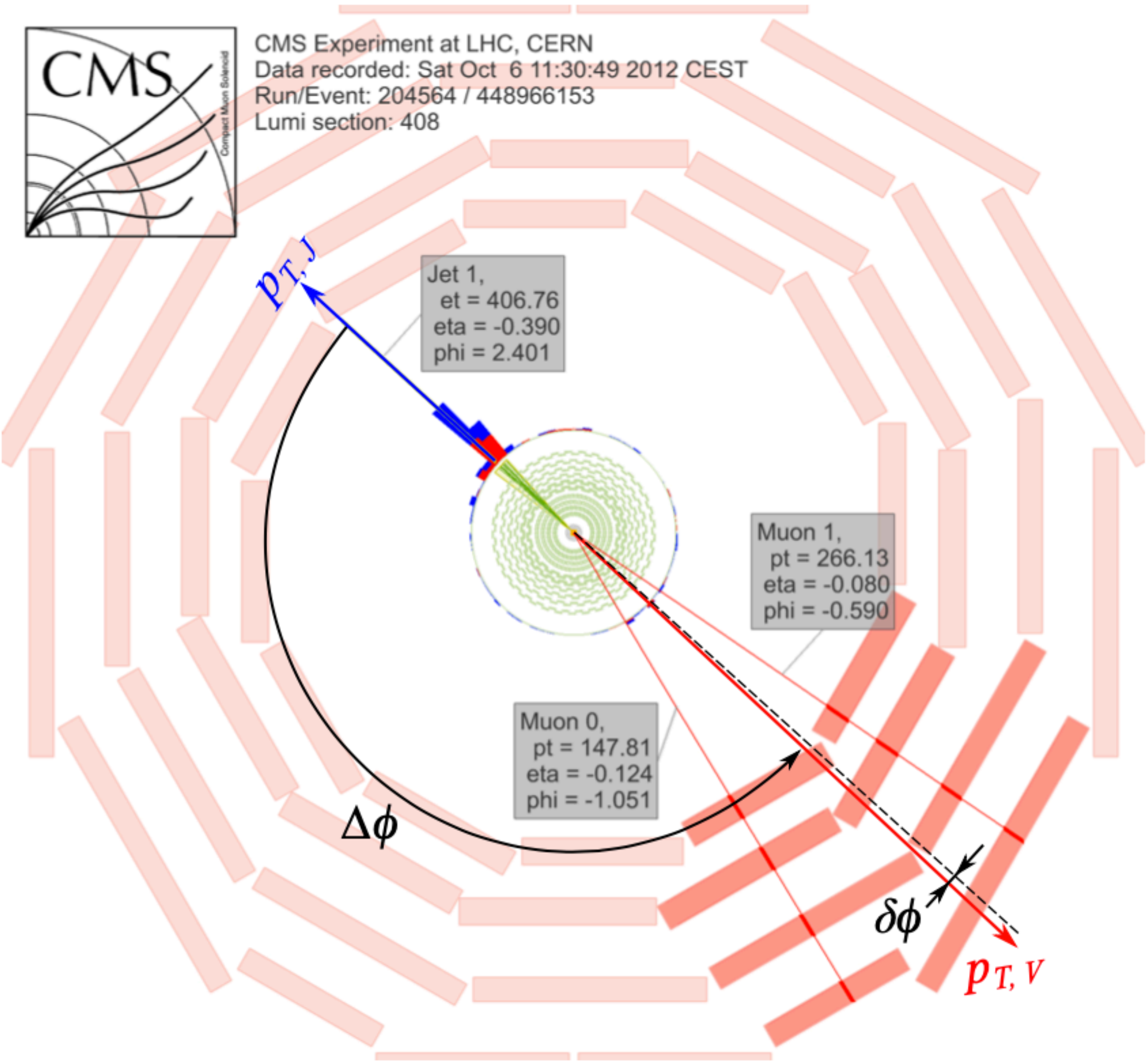
In collaboration with Rudi Rahn, Solange Schrijnder van Velzen, Ding Yu Shao, Wouter J. Waalewijn, Bin Wu

Outline

- Boson+jet process and the observable $\Delta\phi$
  - Recoil free definition
- Monte Carlo studies
- Factorization and resummation in SCET
  - Linear polarized gluon contributions
- Comparison to MC

Boson-jet azimuthal decorrelation

Definition: $\Delta\phi \equiv |\phi_V - \phi_J|$ $(\delta\phi \equiv \pi - \Delta\phi)$: a stringent test of QCD in pp



Precise predictions rely on

1. Fixed-order calculations

   NLO, NNLO,$\cdots$

2. Resummation of $\ln\delta\phi$

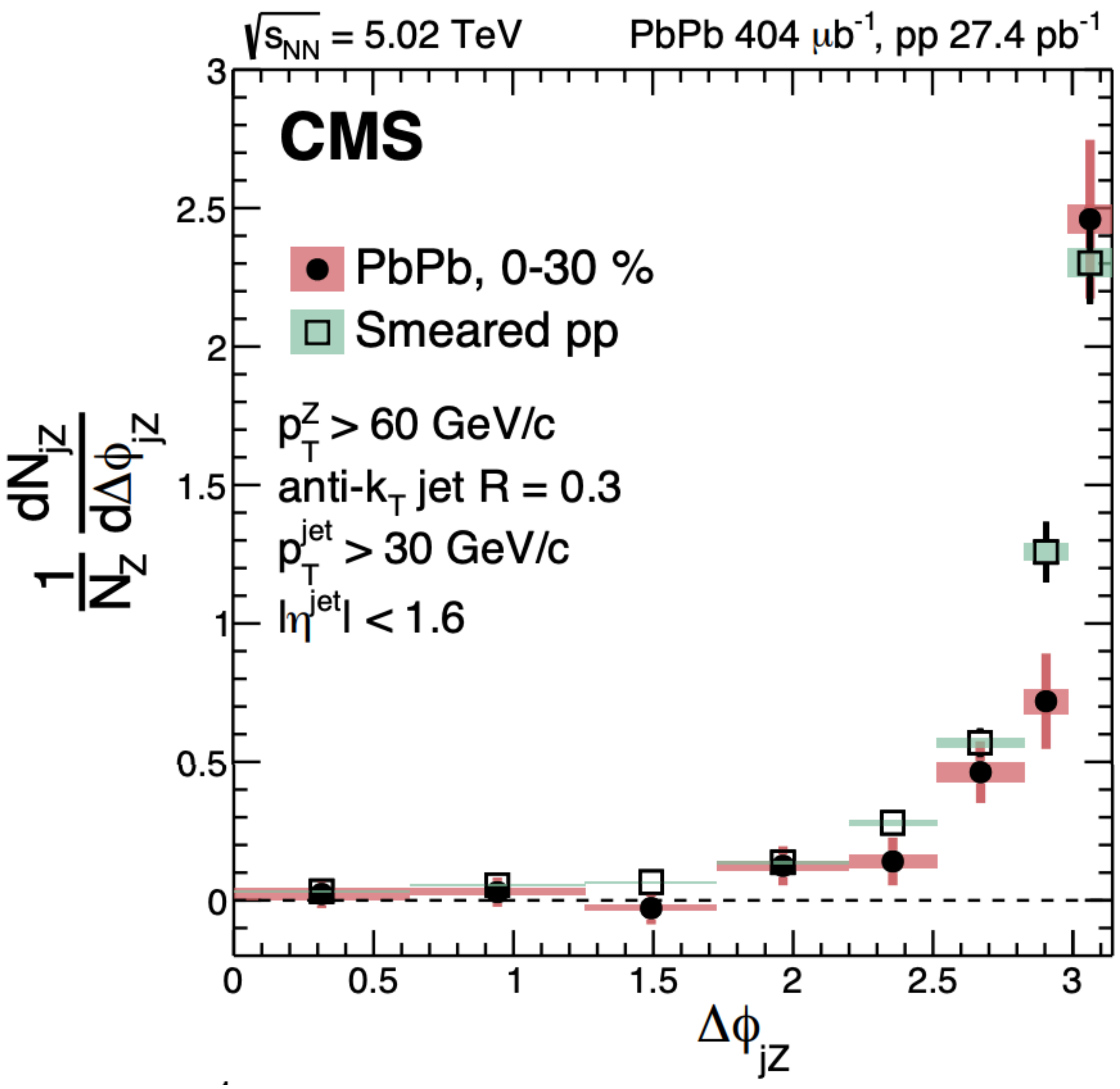
   - Parton branching method
   - Pythia, Herwig,$\cdots$
   - TMD factorization
   - SCET

3. Validity of factorziation

   Is it broken by Glauber modes?

Bin Wu, presented at DESY

Probing quark-gluon plasma

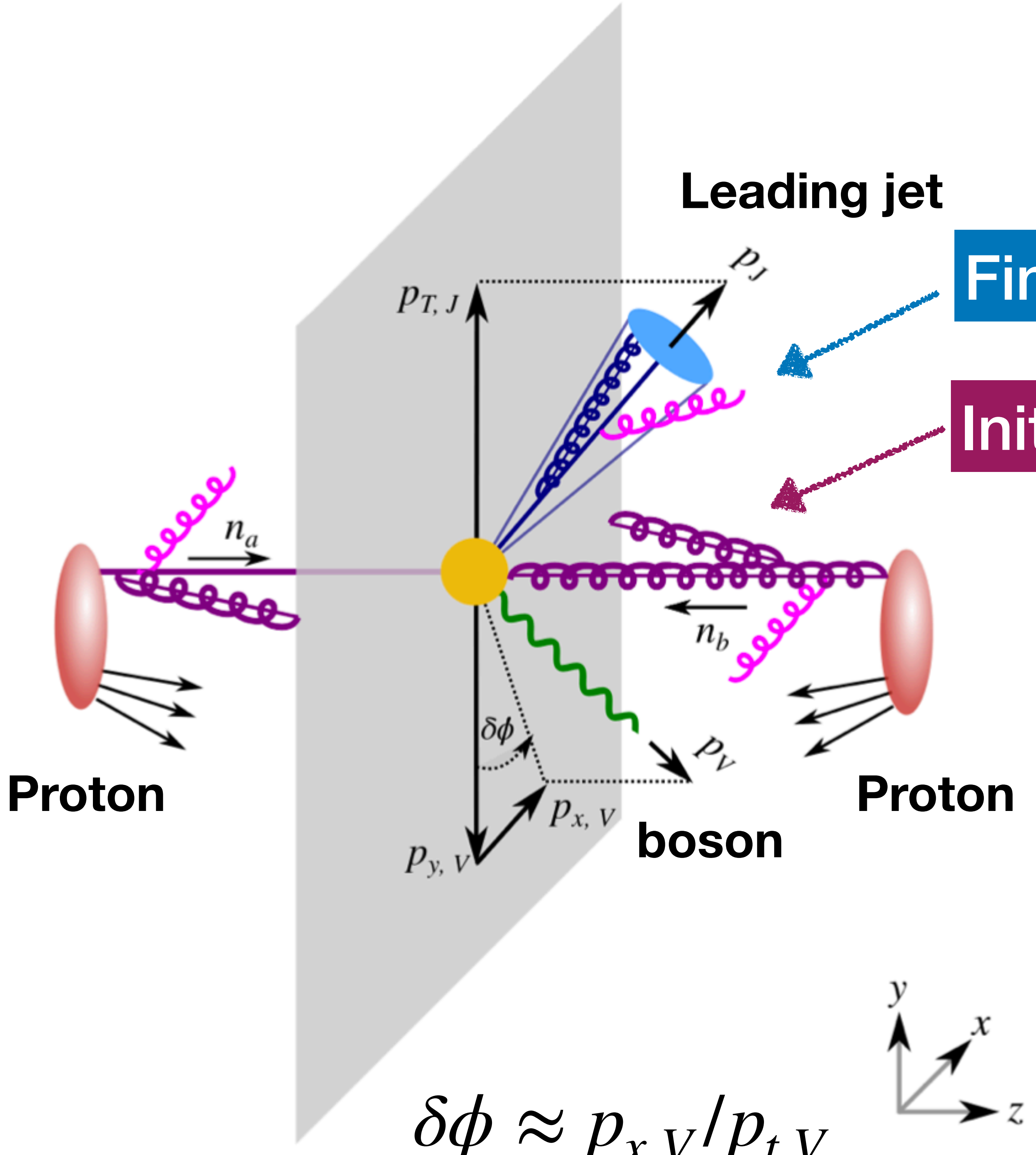


PRL 119, 082301 (2017)

- Due to jet medium interaction, one expects that jets will be deflected when they pass through QGP
- There is a huge underlying event in AA collisions which affects conventional jet reconstruction
- “Smeared pp” and (smeared) PbPb may have just lost the sensitivity to probe QGP properties

We hope to convince you that a “recoil free” definition is theoretically and experimentally cleaner

Boson+jet process

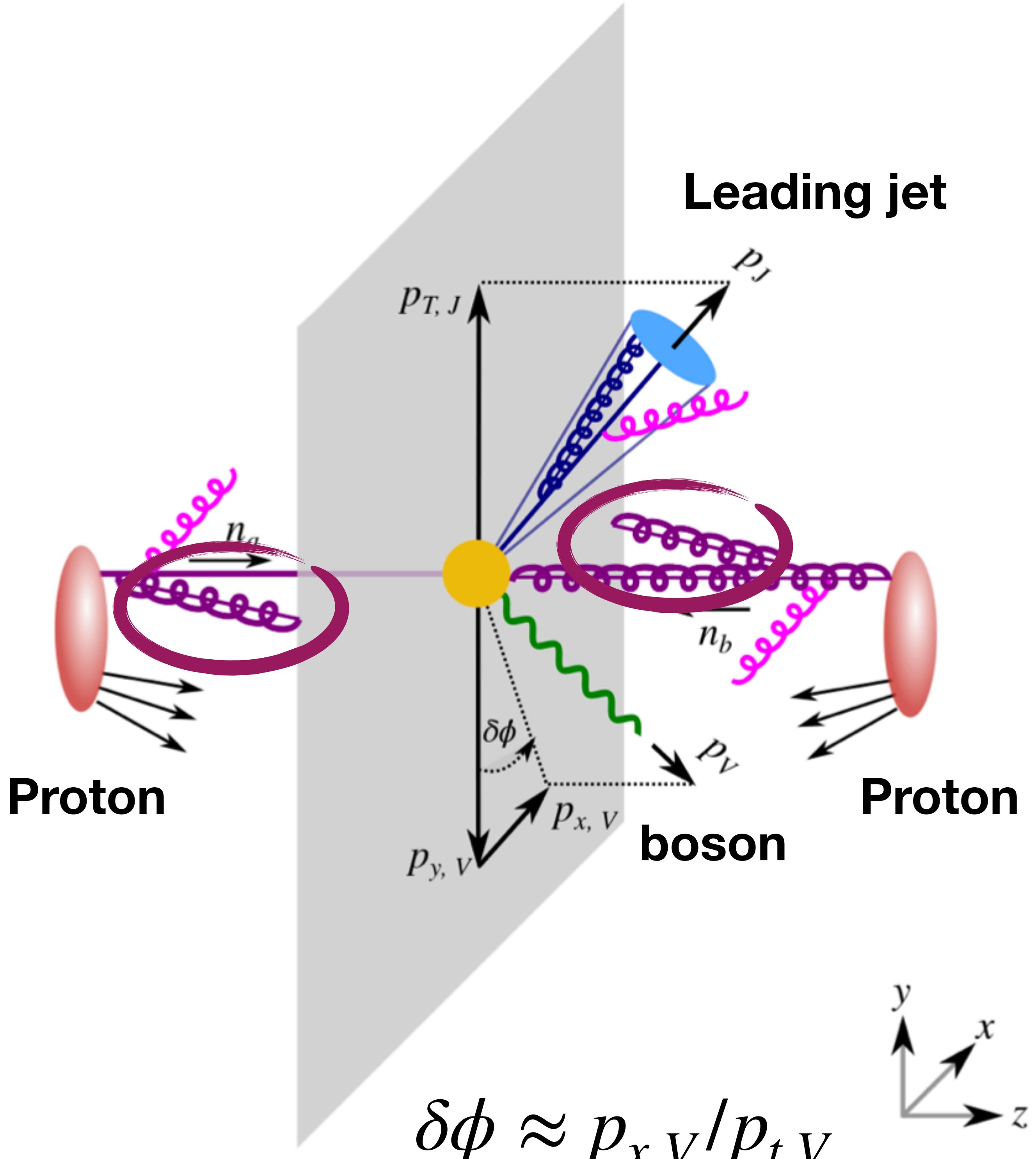


Final state radiation

Initial state radiation

$$\delta\phi \approx p_{x,V}/p_{t,V}$$

Boson+jet process

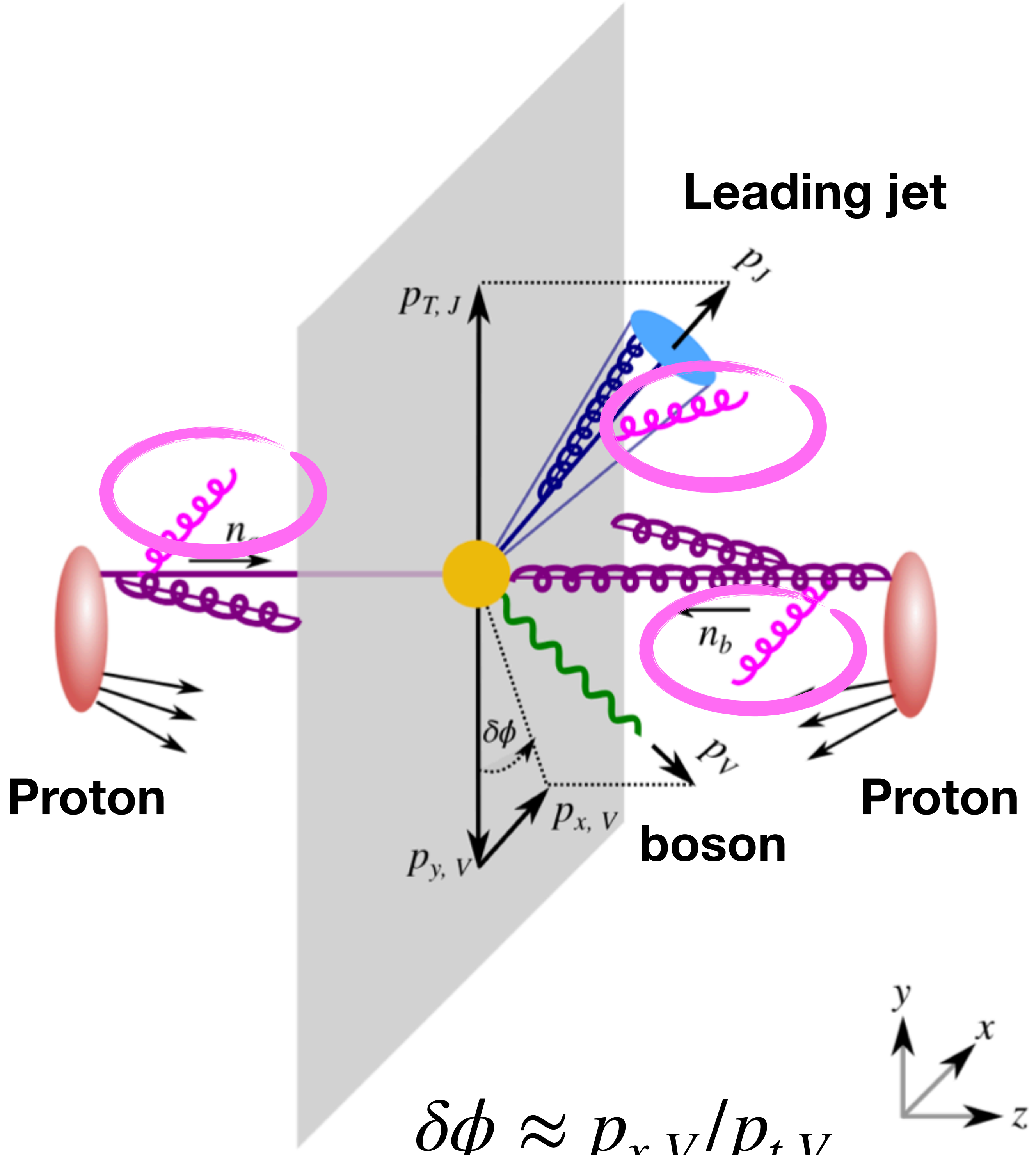


$$\delta\phi \approx p_{x,V}/p_{t,V}$$

Collinear radiation along beams

Therefore the initial partons can have nonzero transverse momentum before hard collision

Boson+jet process



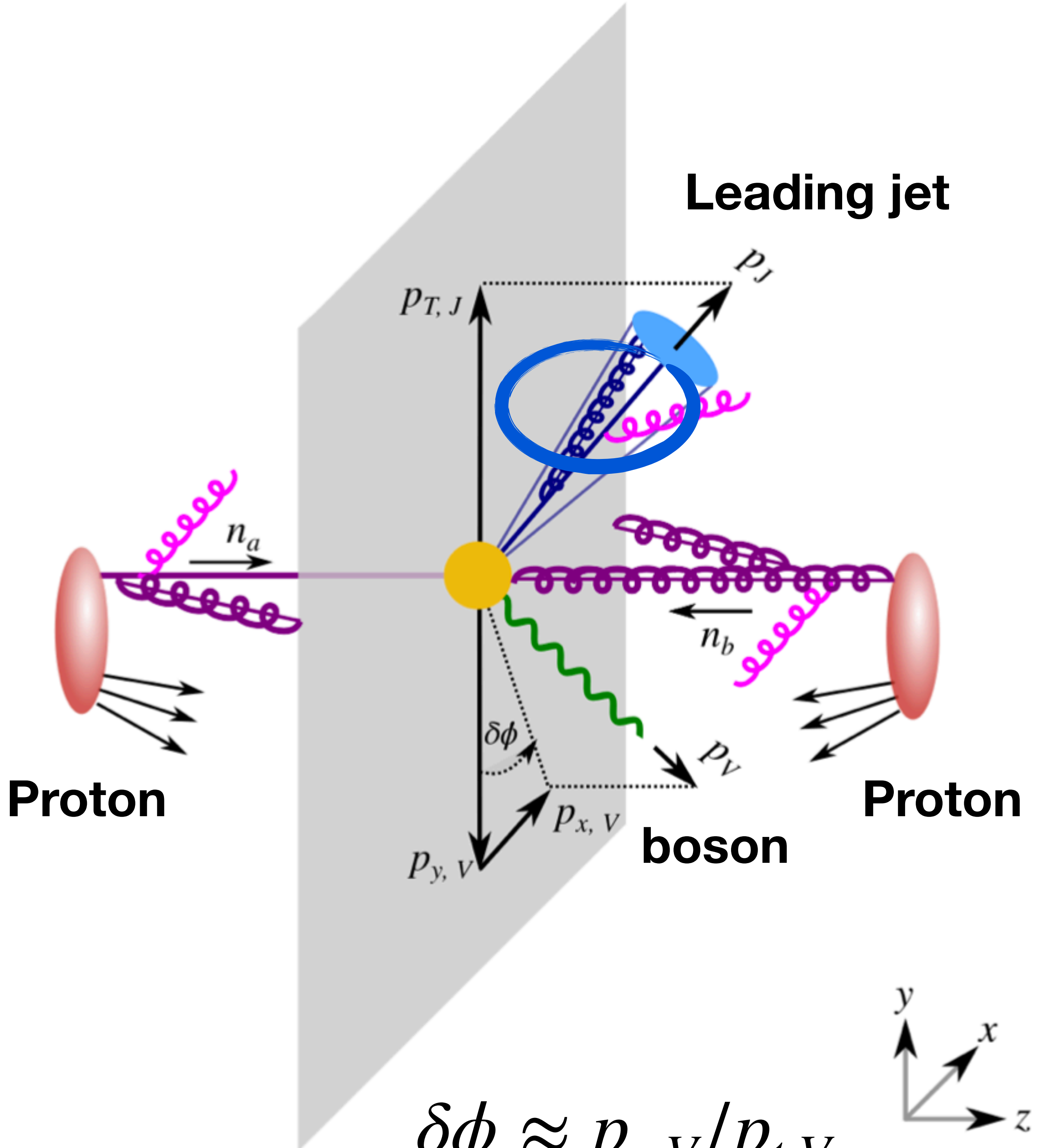
$$\delta\phi \approx p_{x,V}/p_{t,V}$$

Collinear radiation along beams

Soft radiation everywhere

which can deflect WTA axis and hard process through recoil

Boson+jet process



$$\delta\phi \approx p_{x,V}/p_{t,V}$$

Collinear radiation along beams

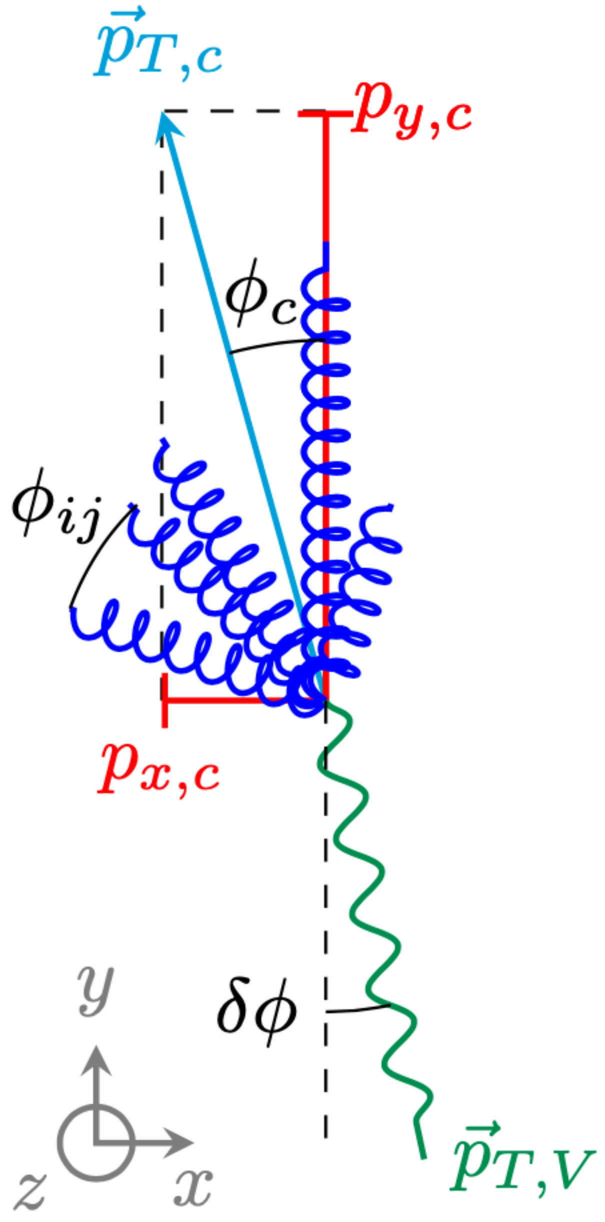
Soft radiation everywhere

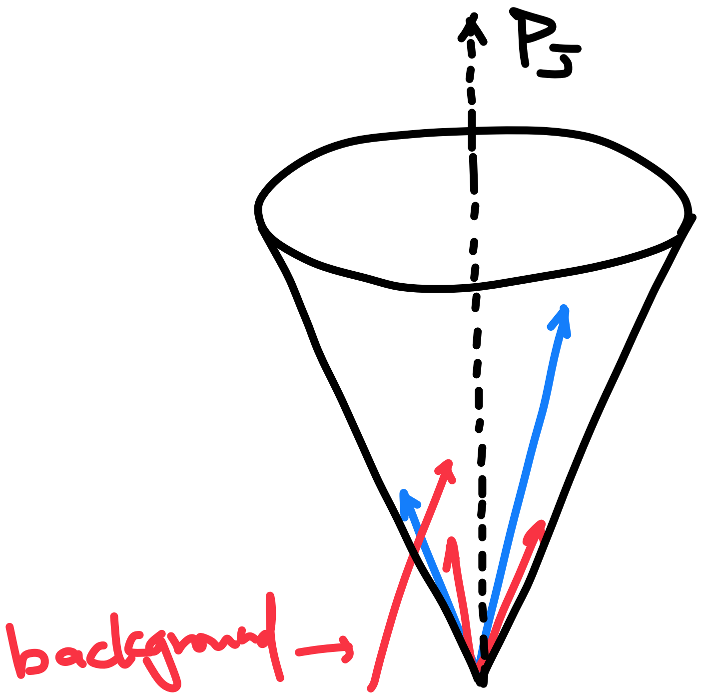
Collinear splitting

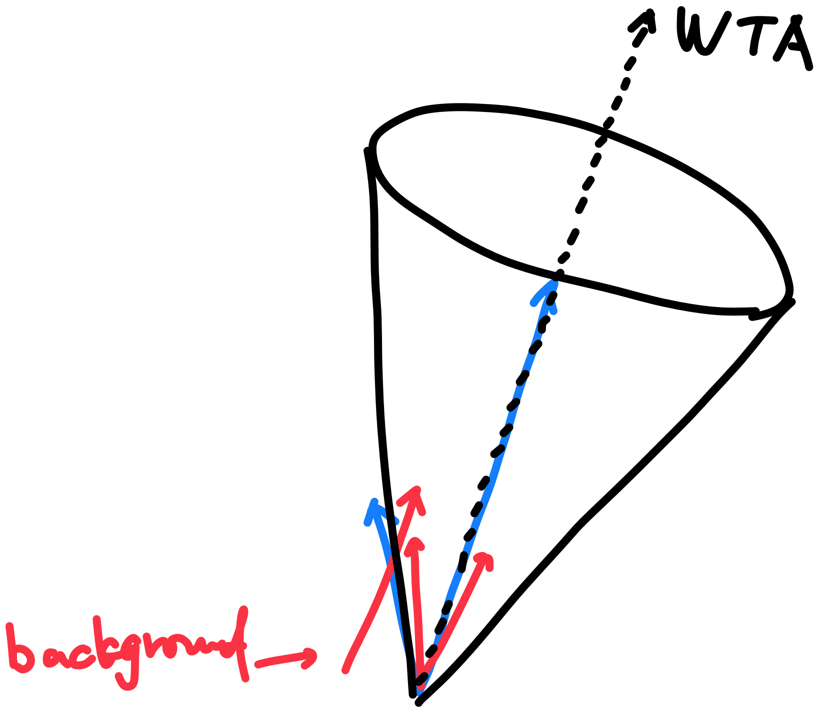
which can deflect WTA axis through recoil

Momentum conserving recoil is always there and we will see that standard jet axis and recoil free axis have different contributions

Standard jet axis and recoil free jet axis







$P_J = P_{\text{collinear}} + P_{\text{soft}}$

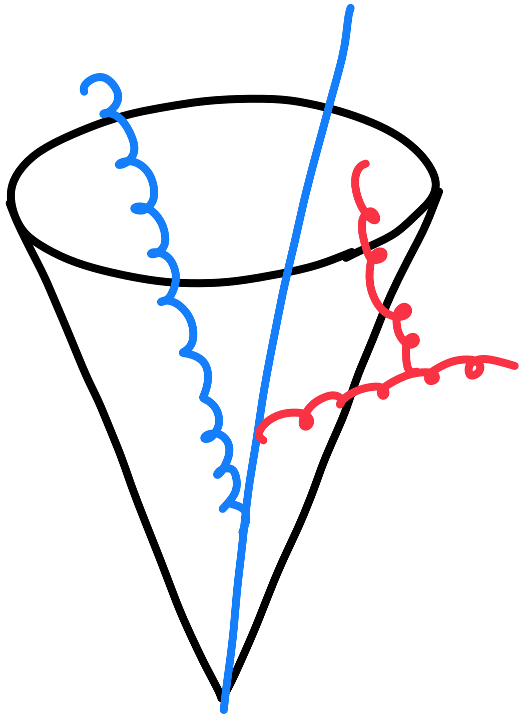
Standard jet axis along P_J, which is the "average" direction of all particles within jet

Winner-Take-All (WTA) axis along dominant energy flow and is not sensitive to soft radiation

In this sense it is called recoil free

Nonglobal contribution for SJA

For standard jet axis, particles inside or outside the jet all make a differenc
so one has to be careful to keep track of soft particles inside jet.

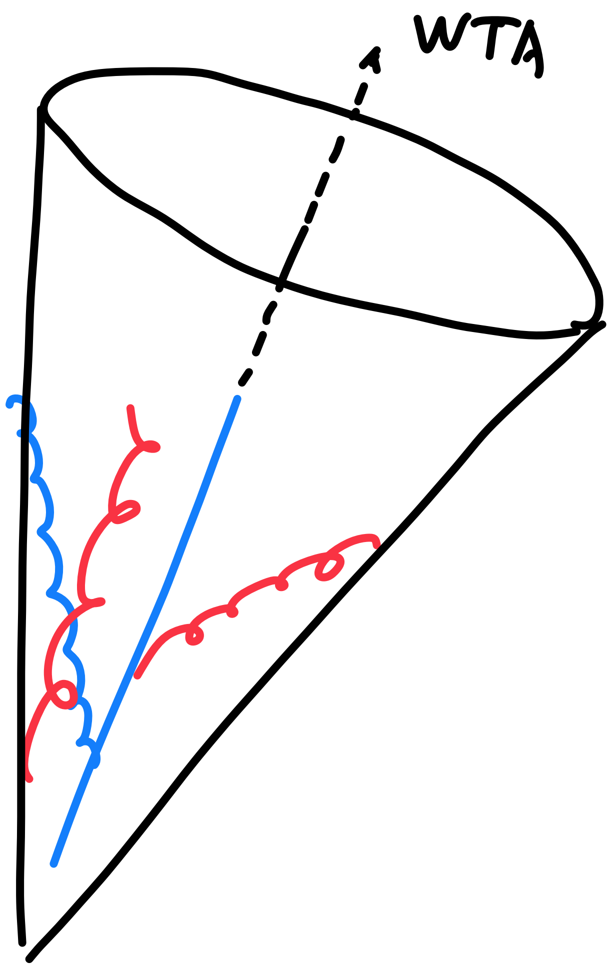


Contribution like this is sensitive to jet boundary and introduces non-global logarithms which need to be resummed : NOT easy ! And this limits the theoretical precision to NLL.

Dasgupta & Salam Phys. Lett. B 512 323-330 (2001)
+ many follow-up work in the past 20 years

Chen, Shao, Wu
JHEP 11 (2019) 025

No nonglobal contribution for WTA

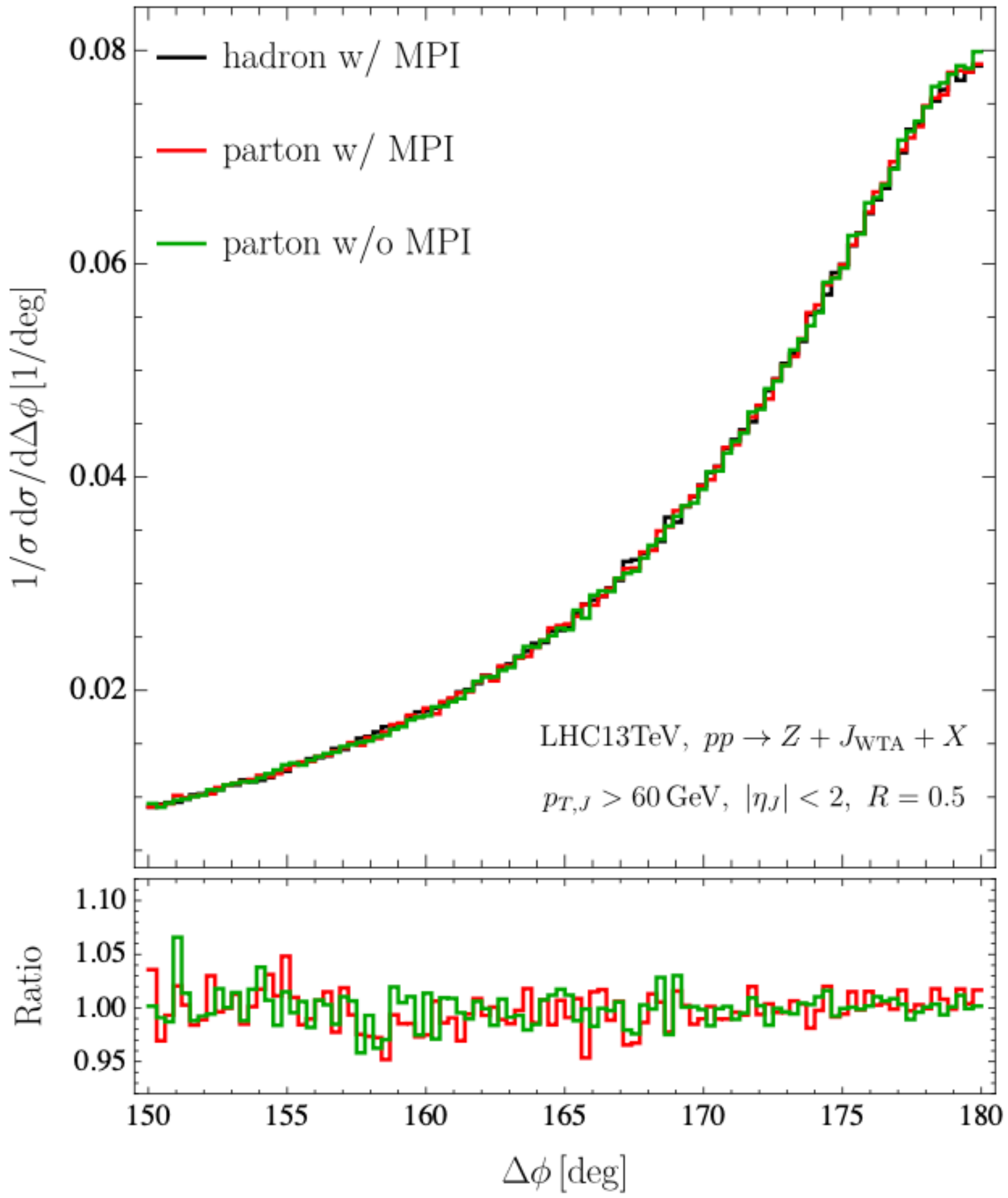


WTA is along the dominant energy flow with jets, and in fact it has recoil contributions from ALL collinear splitting and soft radiation. So WTA axis is NOT sensitive to jet boundary and has no nonglobal contribution.

In some sense, WTA axis has "maximum" recoil contribution. The recoil-free terminology refers to observable definitions and sensitivity to background.

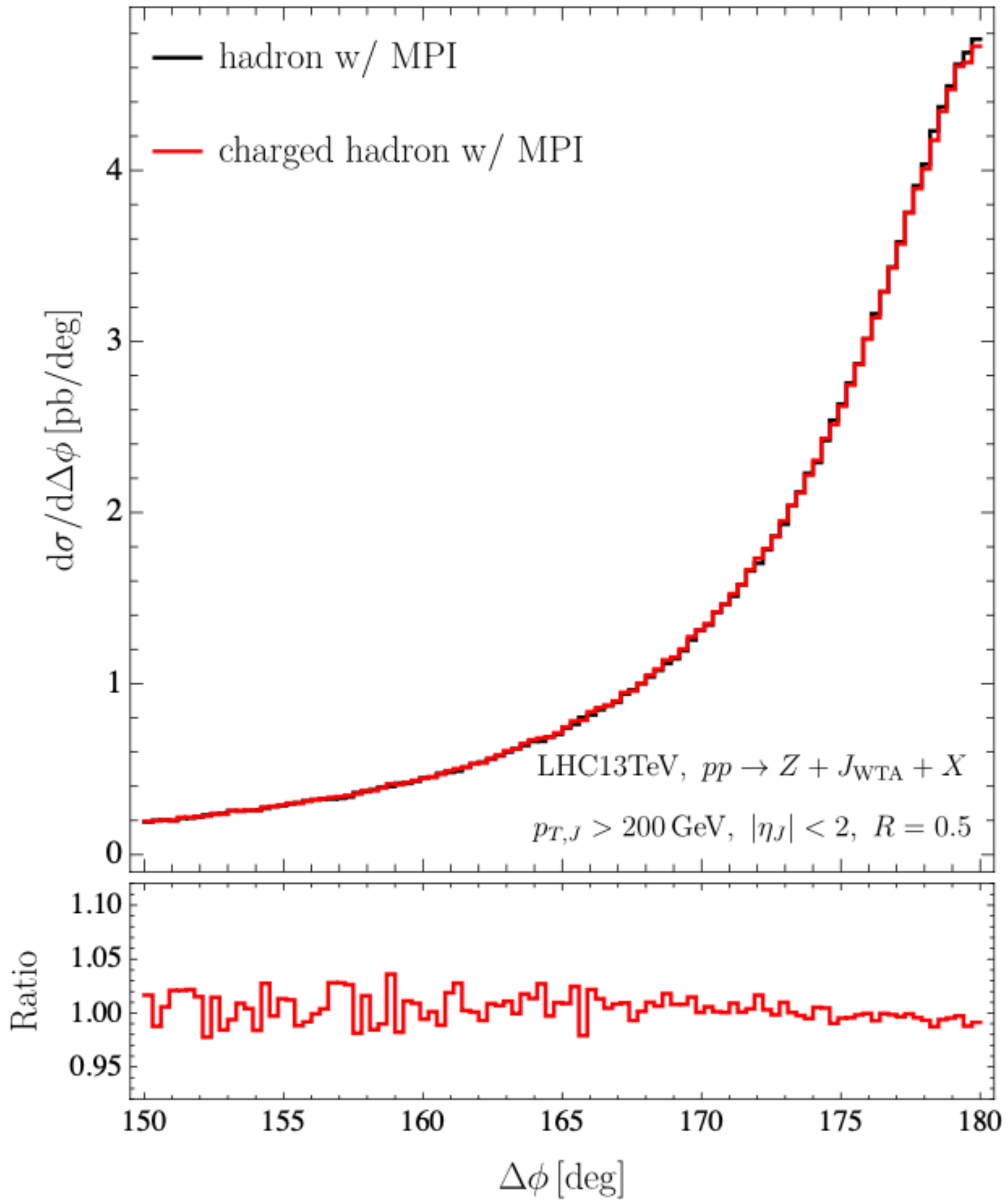
So we will be able to extend the theory precision to NNLL or even NNNLL!

Hadronization, multi-parton interaction and charge tracks



WTA axis insensitive to hadronization and multi-parton interaction.

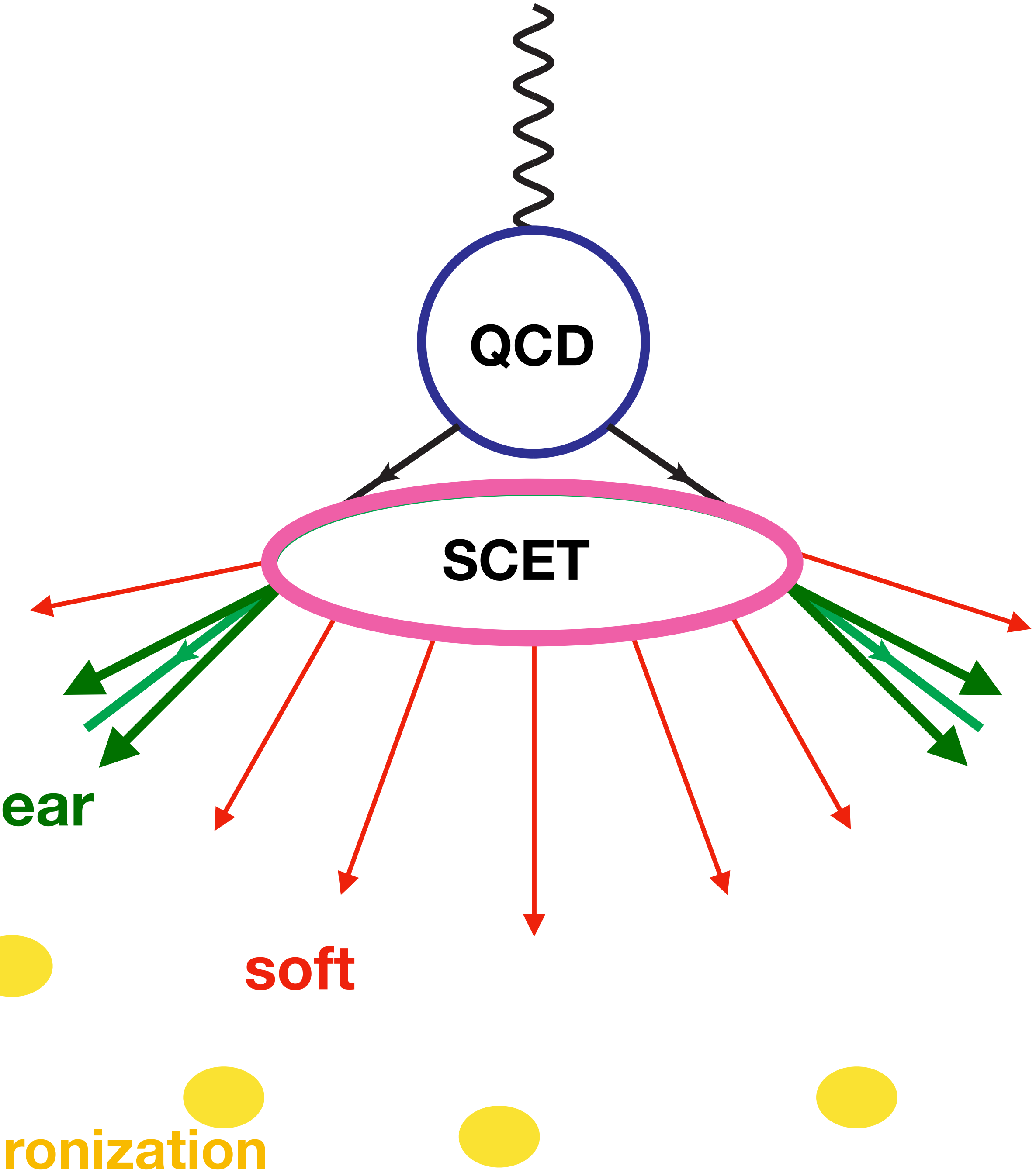
Also insensitive to pileup and heavy ion background.

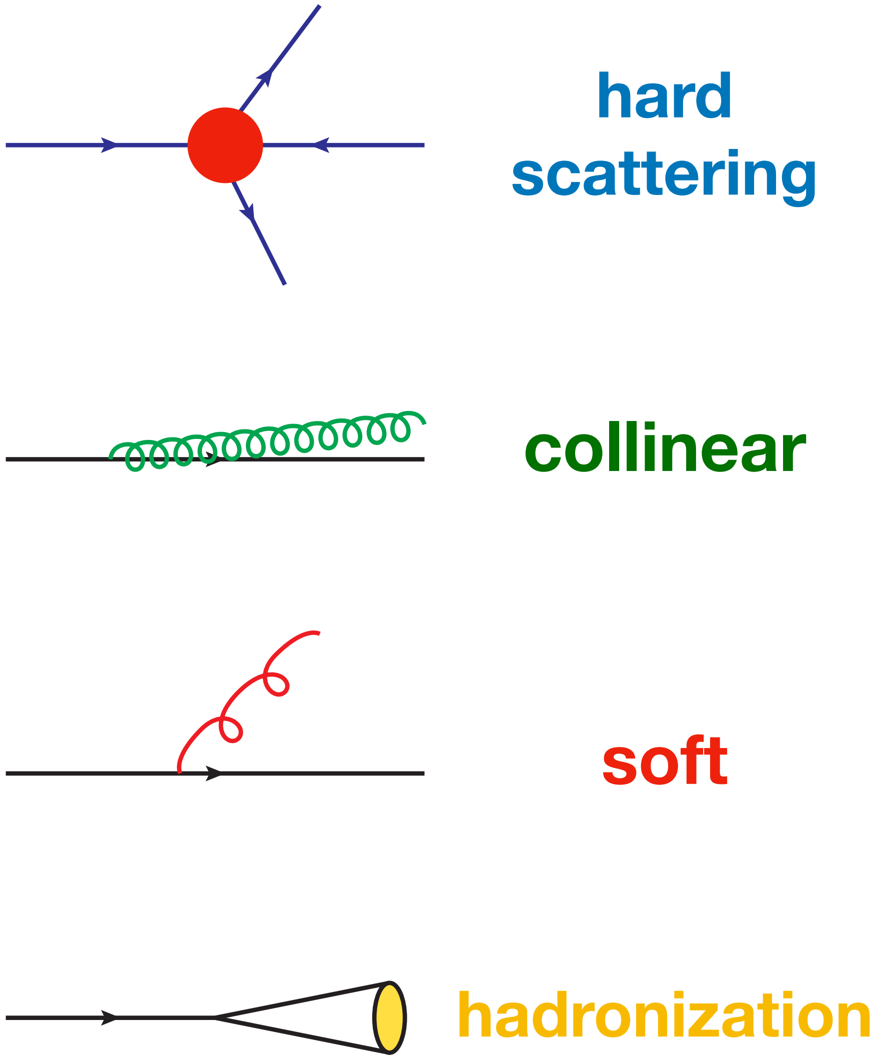


Can exploit the high angular resolution of charge tracks.

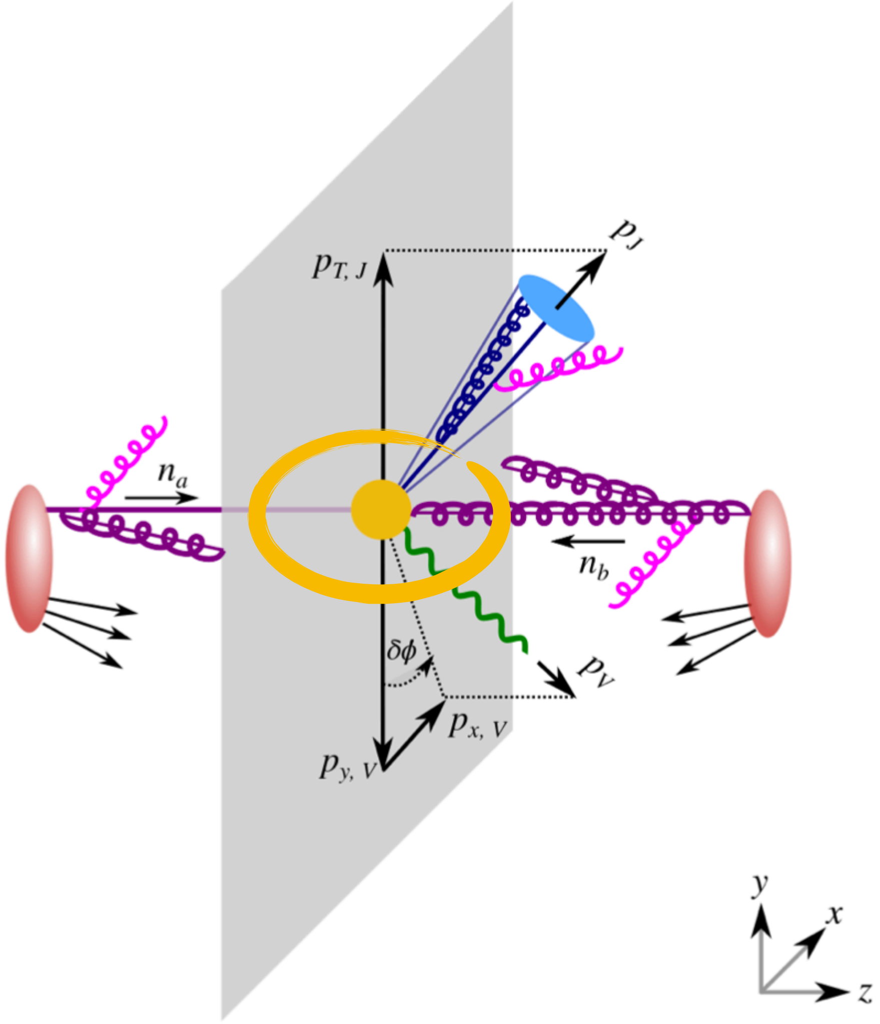
Soft Collinear Effective Theory

Bauer, Fleming, Pirjol, Stewart, PRD 63, 114020 (2001)





Factorization

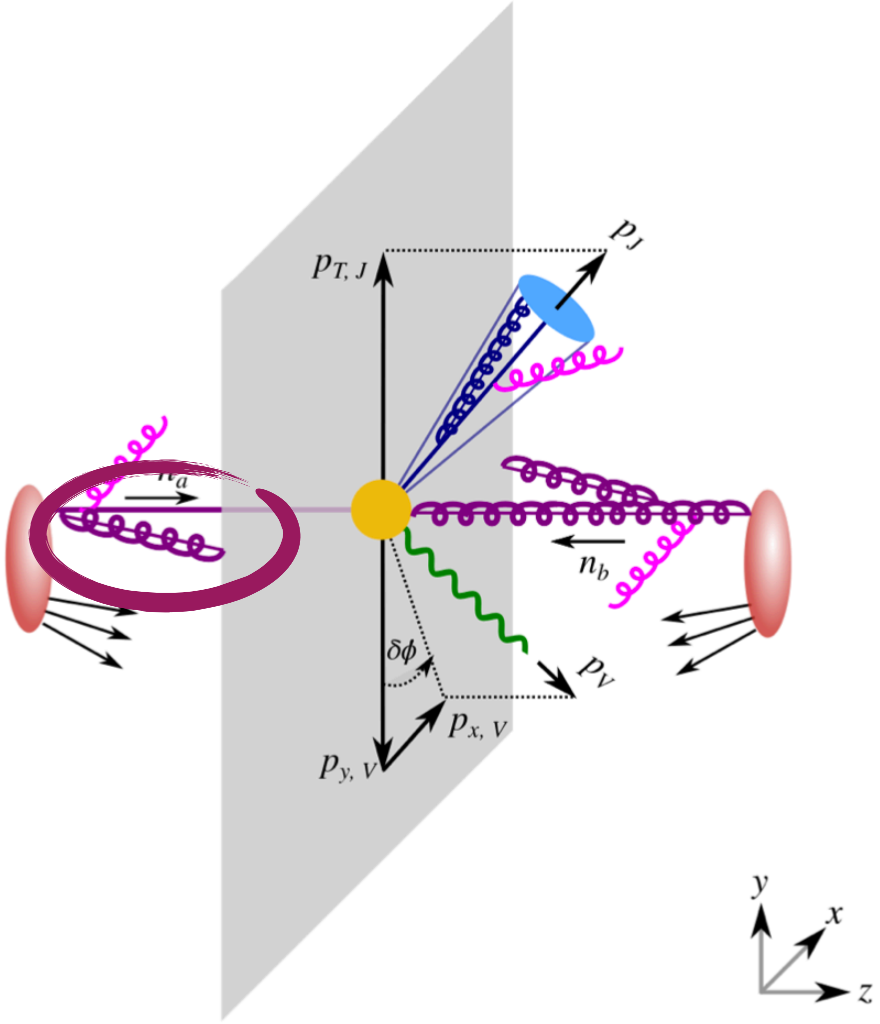


Hard function describes the high momentum transfer process

$$\frac{\mathrm{d}\sigma_{\mathrm{resum}}}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\mathrm{d}y_V} = \sum_{ijk}\int_0^\infty \frac{\mathrm{d}b_x}{\pi}\cos(b_x q_x)\prod_{a=ijk}\left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{Ba}(\mu_B)}\exp\left(\int_{\mu_H}^{\mu_B}\frac{\mathrm{d}\mu}{\mu}\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)$$
$$\times\,\mathcal{H}_{ij\to kV}(p_{T,V}, y_V - y_J, \mu_H)\mathcal{B}_i(x_1, b_x, \mu_B, \nu_i)\mathcal{B}_j(x_2, b_x, \mu_B, \nu_j)$$
$$\times\,\mathcal{J}_k(b_x, \mu_B, \nu_k)\mathcal{S}_{ijk}(b_x, \mu_B, \nu_S)\,,$$

x_i momentum fraction

Factorization



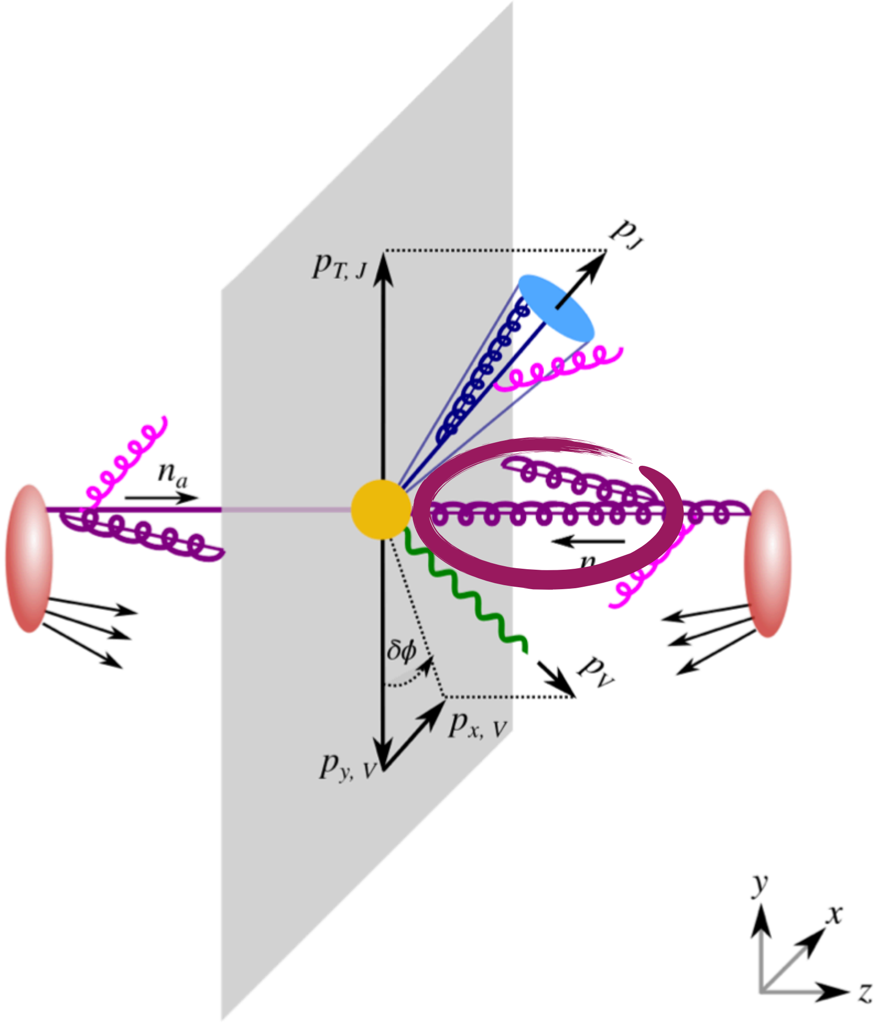
Hard function describes the
high momentum transfer process

Beam functions describe the
collinear emissions along beams

$$\frac{\mathrm{d}\sigma_{\mathrm{resum}}}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\mathrm{d}y_V} = \sum_{ijk}\int_0^\infty \frac{\mathrm{d}b_x}{\pi}\cos(b_x q_x)\prod_{a=ijk}\left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{Ba}(\mu_B)}\exp\left(\int_{\mu_H}^{\mu_B}\frac{\mathrm{d}\mu}{\mu}\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)$$
$$\times\,\mathcal{H}_{ij\to kV}(p_{T,V}, y_V - \eta_J, \mu_H)\,\mathcal{B}_i(x_1, b_x, \mu_B, \nu_i)\,\mathcal{B}_j(x_2, b_x, \mu_B, \nu_j)$$
$$\times\,\mathscr{J}_k(b_x, \mu_B, \nu_k)\,S_{ijk}(b_x, \mu_B, \nu_S),$$

x_i momentum fraction

Factorization



Hard function describes the high momentum transfer process

Beam functions describe the collinear emissions along beams

$$\frac{\mathrm{d}\sigma_{\mathrm{resum}}}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\mathrm{d}y_V} = \sum_{ijk}\int_0^\infty \frac{\mathrm{d}b_x}{\pi}\cos(b_x q_x)\prod_{a=ijk}\left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{Ba}(\mu_B)}\exp\left(\int_{\mu_H}^{\mu_B}\frac{\mathrm{d}\mu}{\mu}\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)$$
$$\times\,\mathcal{H}_{ij\to kV}(p_{T,V},y_V-\eta_J,\mu_H)\mathcal{B}_i(x_1,b_x,\mu_B,\nu_i)\mathcal{B}_j(x_2,b_x,\mu_B,\nu_j)$$
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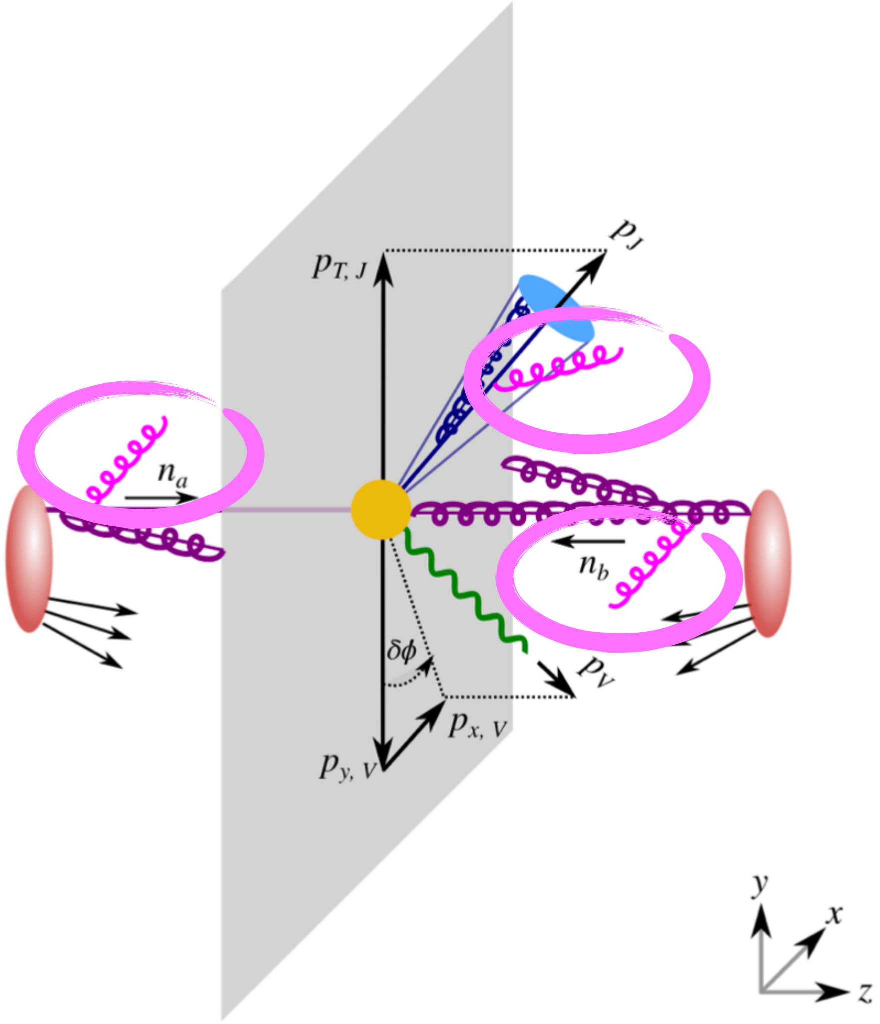
x_i momentum fraction

Factorization



Hard function describes the high momentum transfer process

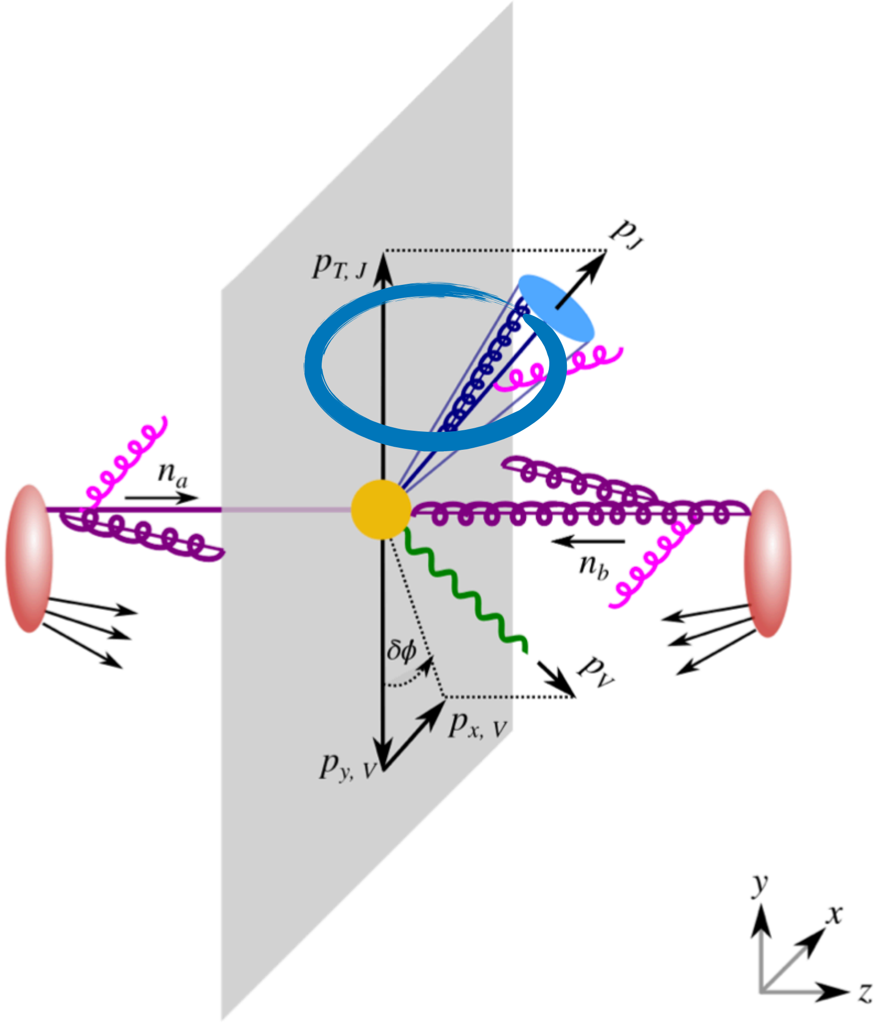
Beam functions describe the collinear emissions along beams

Soft function describes the soft emissions from beams and jets

$$\frac{\mathrm{d}\sigma_{\mathrm{resum}}}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\mathrm{d}y_V} = \sum_{ijk}\int_0^\infty \frac{\mathrm{d}b_x}{\pi}\cos(b_x q_x)\prod_{a=ijk}\left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{Ba}(\mu_B)}\exp\left(\int_{\mu_H}^{\mu_B}\frac{\mathrm{d}\mu}{\mu}\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)$$
$$\times\, \mathcal{H}_{ij\to kV}(p_{T,V}, y_V - \eta_J, \mu_H)\mathcal{B}_i(x_1, b_x, \mu_B, \nu_i)\mathcal{B}_j(x_2, b_x, \mu_B, \nu_j)$$
$$\times\, \mathscr{J}_k(b_x, \mu_B, \nu_k) S_{ijk}(b_x, \mu_B, \nu_S)$$

x_i momentum fraction

Factorization



Hard function describes the high momentum transfer process

Beam functions describe the collinear emissions along beams

Soft function describes the soft emissions from beams and jet

Jet function describes the collinear splitting inside jet

$$\frac{\mathrm{d}\sigma_{\mathrm{resum}}}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\mathrm{d}y_V} = \sum_{ijk}\int_0^\infty \frac{\mathrm{d}b_x}{\pi}\cos(b_x q_x)\prod_{a=ijk}\left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{Ba}(\mu_B)}\exp\left(\int_{\mu_H}^{\mu_B}\frac{\mathrm{d}\mu}{\mu}\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)$$
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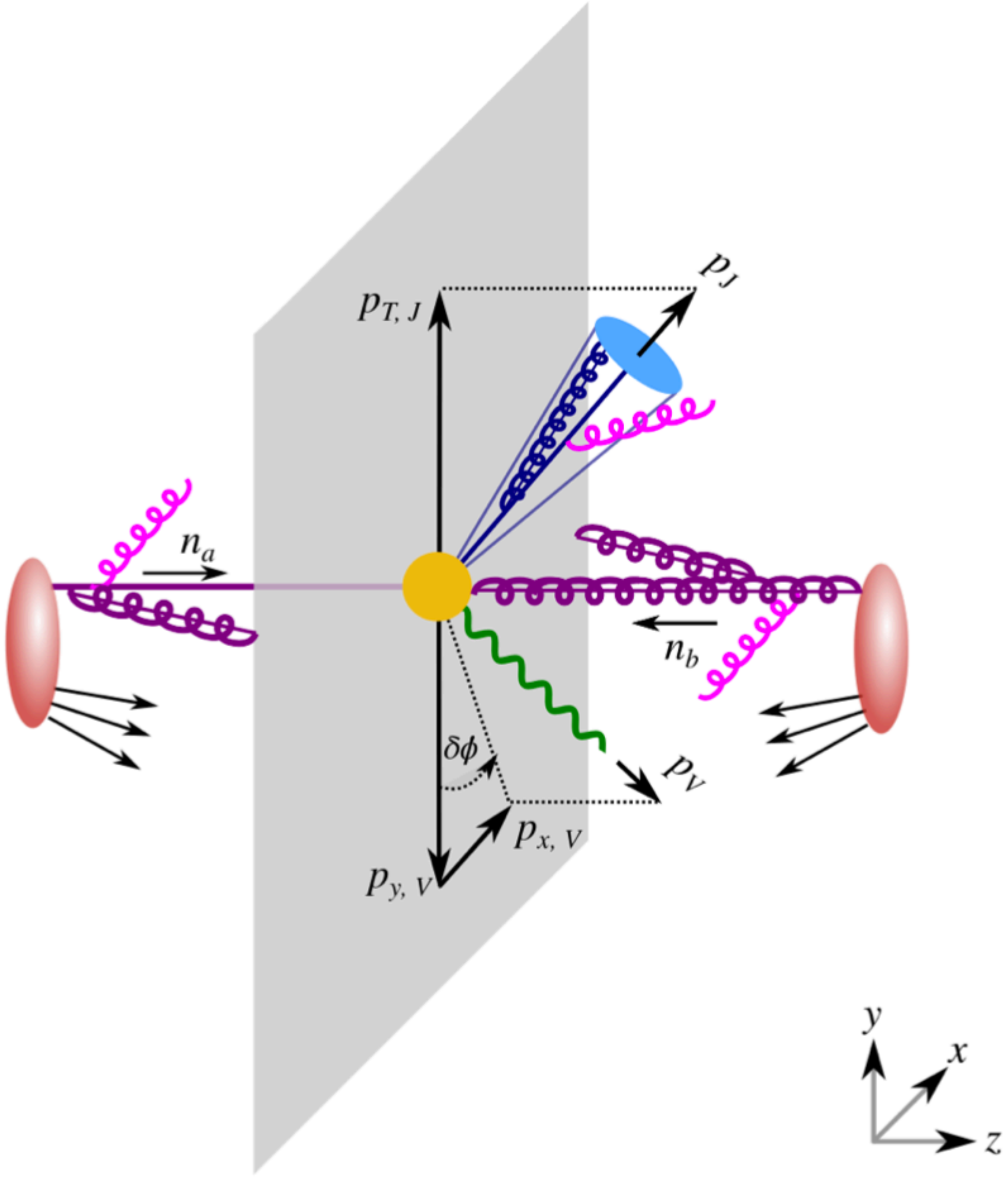
$$\times\,\mathscr{J}_k(b_x,\mu_B,\nu_k)\,\mathcal{S}_{ijk}(b_x,\mu_B,\nu_S)\,,$$

x_i momentum fraction

Characteristic scales



Hard function $m_V,\, p_{tJ}$

Beam function

Soft function $q_x \leftrightarrow 1/b_x$

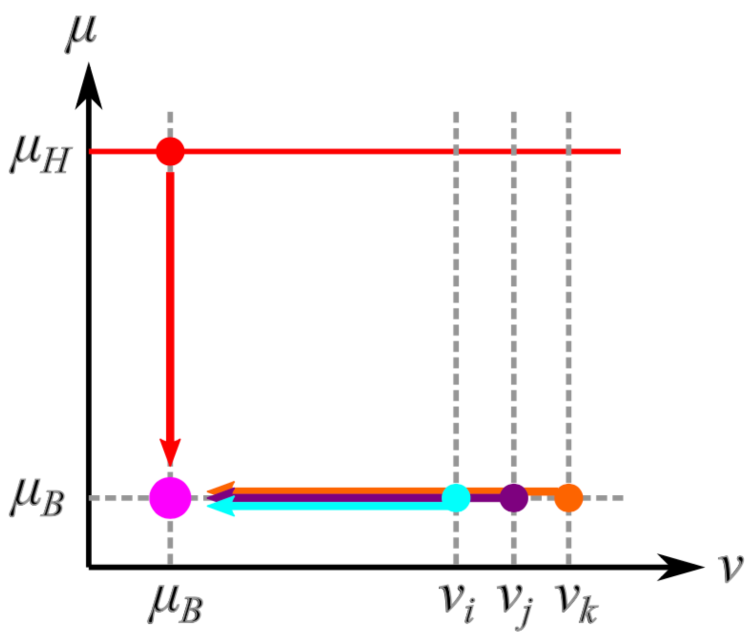
Jet function

Renormalization and resummation

$$\frac{d\sigma_{\text{resum}}}{dq_x\, dp_{T,V} dy_V} = \sum_{ijk} \int_0^\infty \frac{db_x}{\pi} \cos(b_x q_x) \prod_{a=ijk} \left(\frac{\nu_S}{\nu_a}\right)^{\underset{3}{\Gamma_\nu^{Ba}}(\mu_B)} \overset{\text{RG evolution factor}}{\boxed{\exp\left(\int_{\mu_H}^{\mu_B} \frac{d\mu}{\mu} \underset{2}{\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}}(\alpha_s)\right)}}$$

$$\times \mathcal{H}_{ij\to kV}(p_{T,V}, y_V - \eta_J, \mu_H)\mathcal{B}_i(x_1, b_x, \mu_B, \nu_i)\mathcal{B}_j(x_2, b_x, \mu_B, \nu_j)$$

$$\times \mathscr{J}_k(b_x, \mu_B, \nu_k) S_{ijk}(b_x, \mu_B, \nu_S)\,,$$



$$\mu_H = \sqrt{m_V^2 + p_{T,V}^2}\,, \quad \mu_B = \nu_S = 2e^{-\gamma_E}/b_*, \quad \nu_a = \omega_a = \bar{n}_a \cdot p_a\,,$$

$$b_* = |b_x|/\sqrt{1 + b_x^2/b_{\max}^2}$$

b_x prescription, $b_{max} \sim 1.5$ GeV

$$\boxed{\exp\left(\int_{\mu_H}^{\mu_B} \frac{d\mu}{\mu} \Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)}$$

$$= \left(\frac{\hat{u}^2}{p_{T,V}^2 \mu_H^2}\right)^{-C_i A_{\Gamma_{\text{cusp}}}(\mu_H, \mu_B)} \left(\frac{\hat{t}^2}{p_{T,V}^2 \mu_H^2}\right)^{-C_j A_{\Gamma_{\text{cusp}}}(\mu_H, \mu_B)} \left(\frac{p_{T,V}^2}{\mu_H^2}\right)^{-C_k A_{\Gamma_{\text{cusp}}}(\mu_H, \mu_B)}$$

$$\times \exp\left[2(C_i + C_j + C_k) S(\mu_H, \mu_B) - 2 \sum_{a=ijk} A_{\gamma^a}(\mu_H, \mu_B)\right].$$

Hard, beam, jet and soft functions and their anomalous dimensions calculated at 1-loop

Linear polarized gluon contributions

$$\frac{\mathrm{d}\sigma_{\mathrm{resum}}}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\mathrm{d}y_V} = \sum_{ijk}\int_0^\infty \frac{\mathrm{d}b_x}{\pi}\cos(b_x q_x)\prod_{a=ijk}\underset{\text{T \& L}}{\left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{Ba}(\mu_B)}}\exp\Bigg(\int_{\mu_H}^{\mu_B}\underset{\text{T \& L}}{\frac{\mathrm{d}\mu}{\mu}\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)}\Bigg)$$

$$\times\,\mathcal{H}_{ij\to kV}(p_{T,V}, y_V-\eta_J,\mu_H)\mathcal{B}_i(x_1,b_x,\mu_B,\nu_i)\mathcal{B}_j(x_2,b_x,\mu_B,\nu_j)$$

$$\times\,\underset{\text{T \& L}}{\mathscr{J}_k(b_x,\mu_B,\nu_k)}S_{ijk}(b_x,\mu_B,\nu_S)\,,$$

spin-polarization averaged hard function is no longer sufficient.

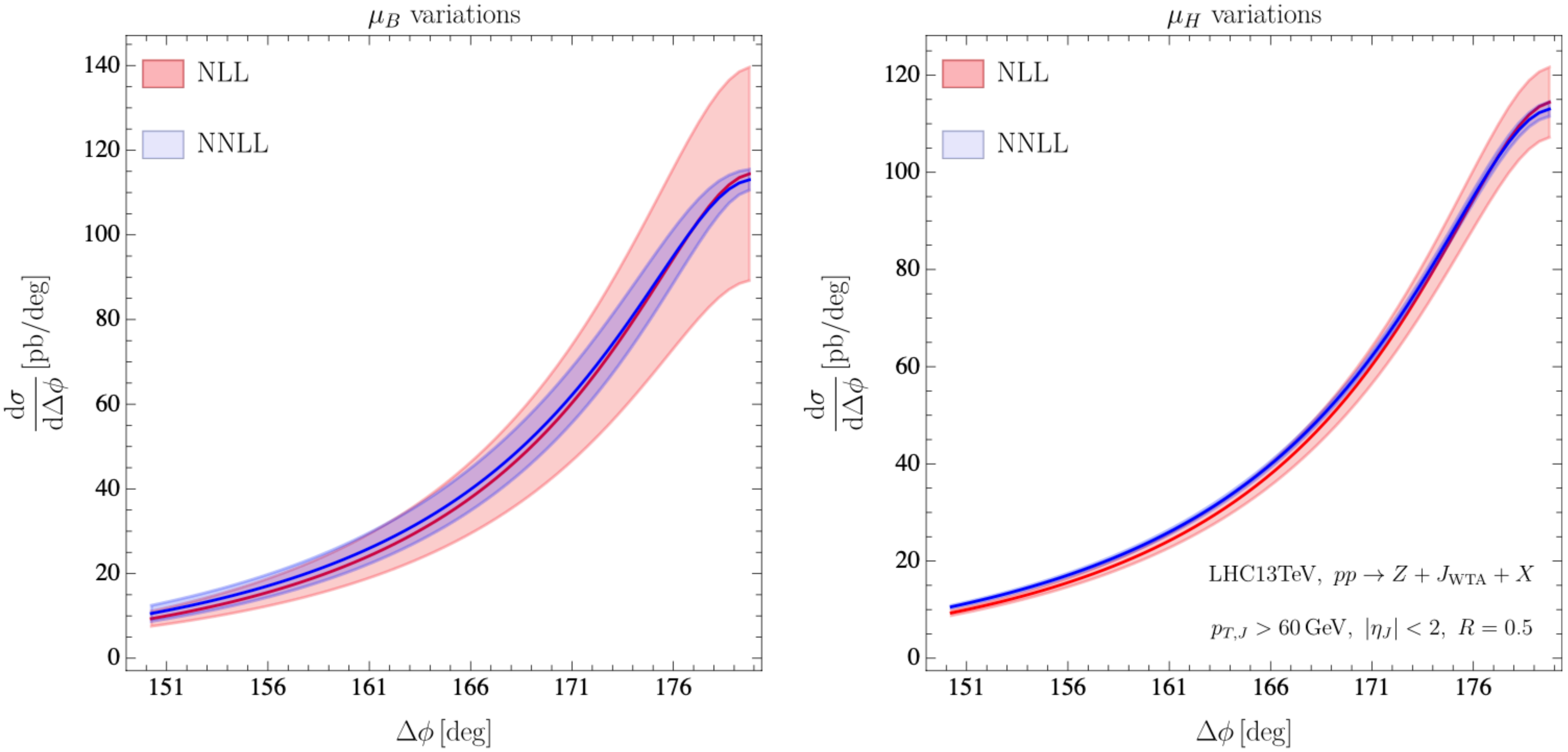
$$B_i(x,b_x,\mu,\nu) = \sum_j\int\frac{\mathrm{d}x'}{x'}\underbrace{\mathcal{I}_{ij}\Big(\frac{x}{x'},b_x,\mu,\nu\Big)}_{\text{transverse and linear polarization contribution}}f_j(x',\mu)\left[1+\mathcal{O}(\Lambda_{\mathrm{QCD}}^2\vec{b}_T^2)\right]$$

Even if beam are unpolarized, gluons are intrinsically polarized.

Catani - Grazzini Nucl. Phys. B 845 (2011) 297-323

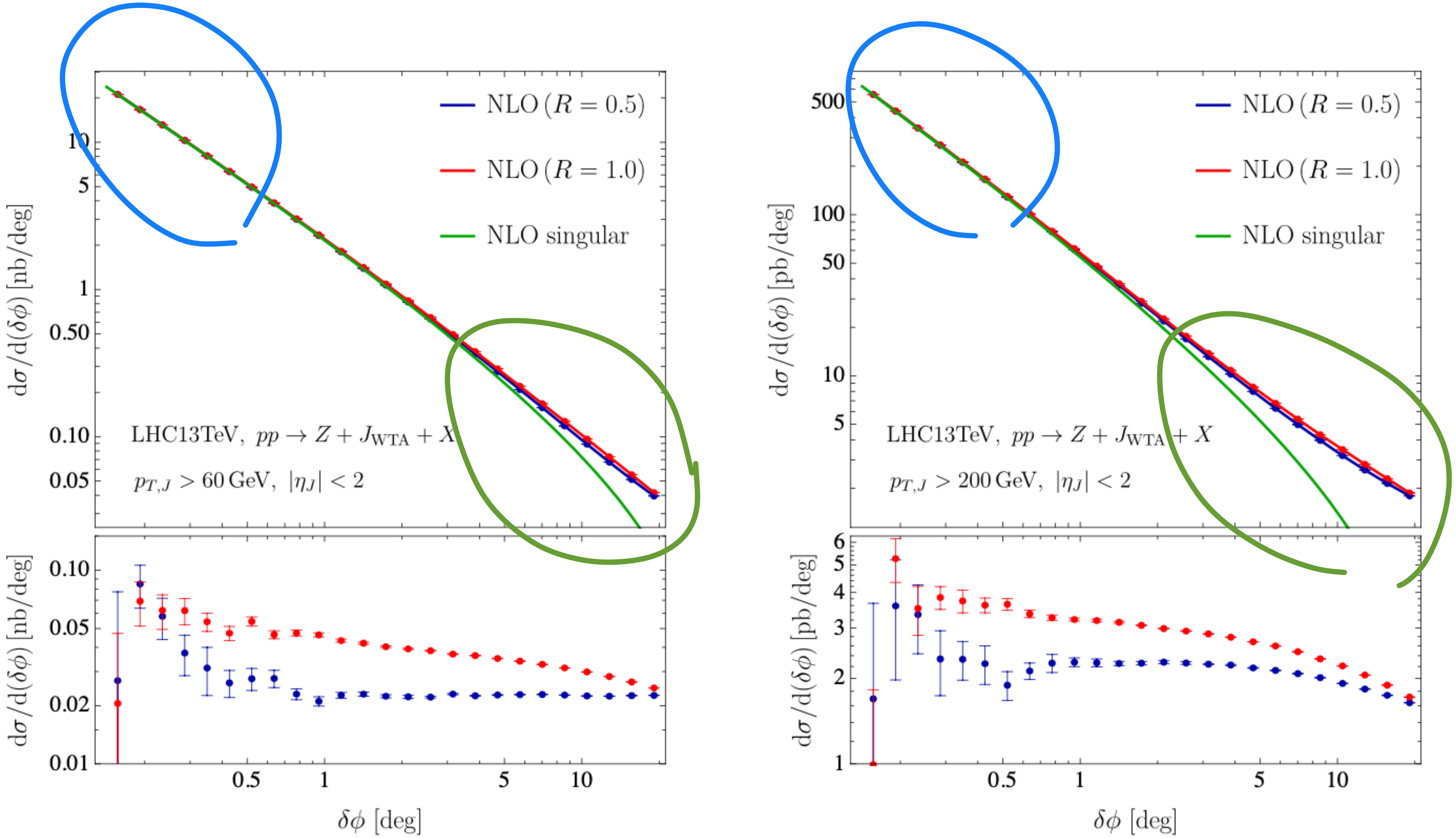
We calculated, for the first time, linear-polarized gluon jet function

From NLL to NNLL



Theory predictions have much better precision.

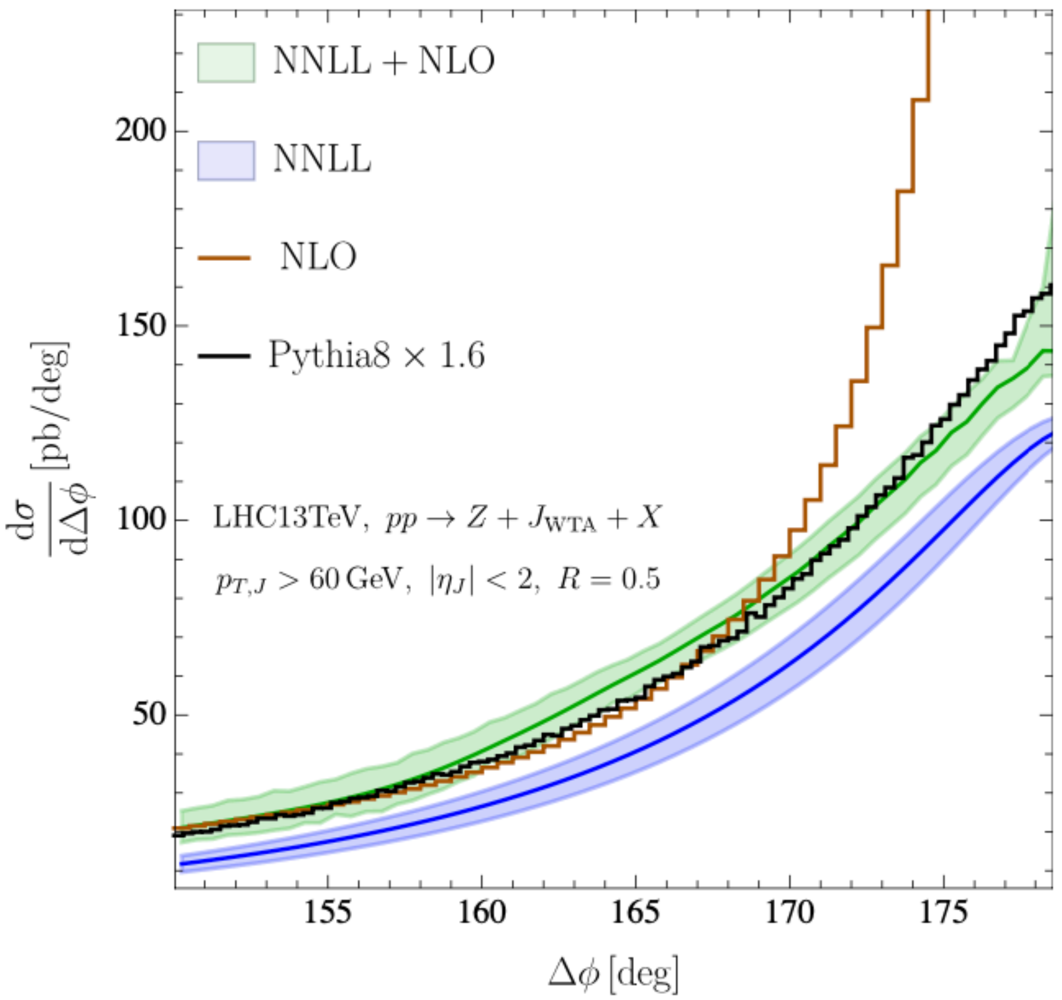
Cross check singular terms with MCFM

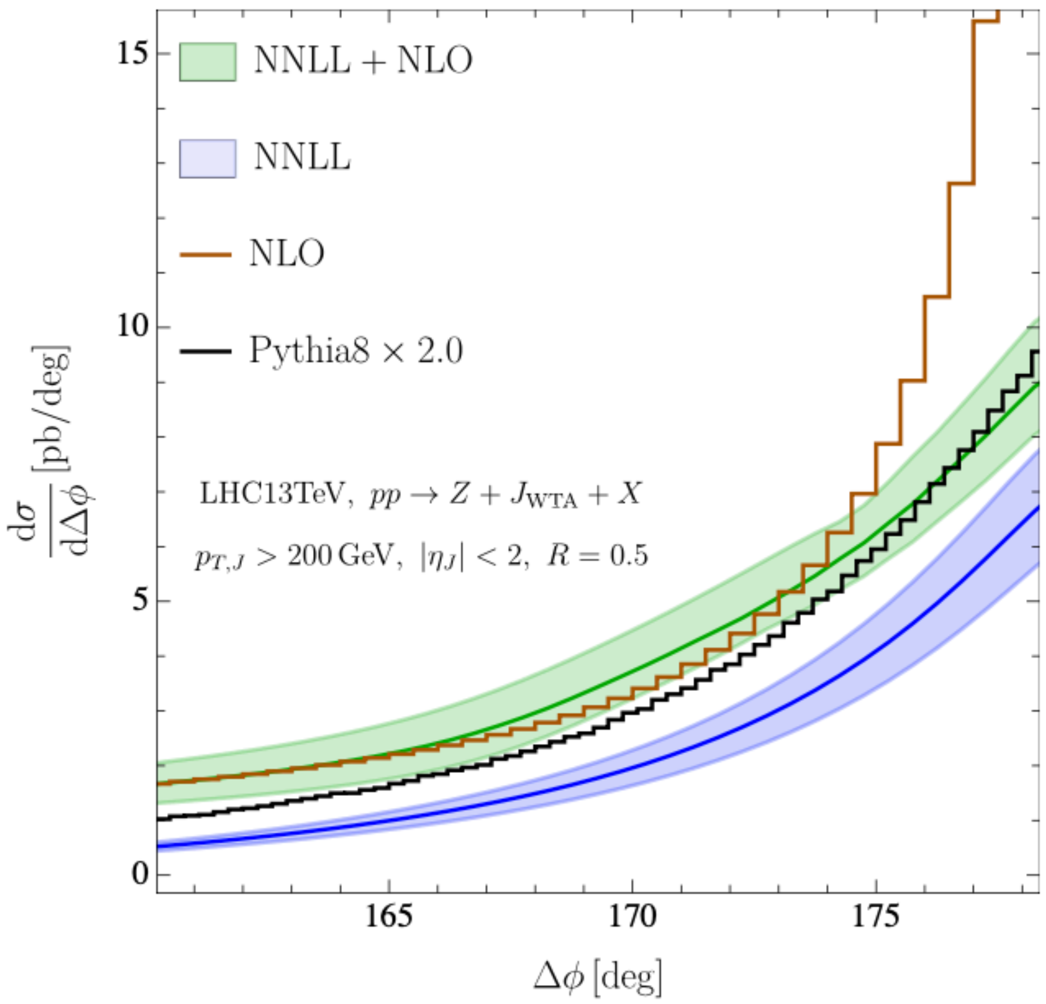


Singular region checked between fixed order calculation and resummed results

Power correction included by matching to fixed order results.
NNLL + (NLO - NLO singular)

Comparison to Pythia

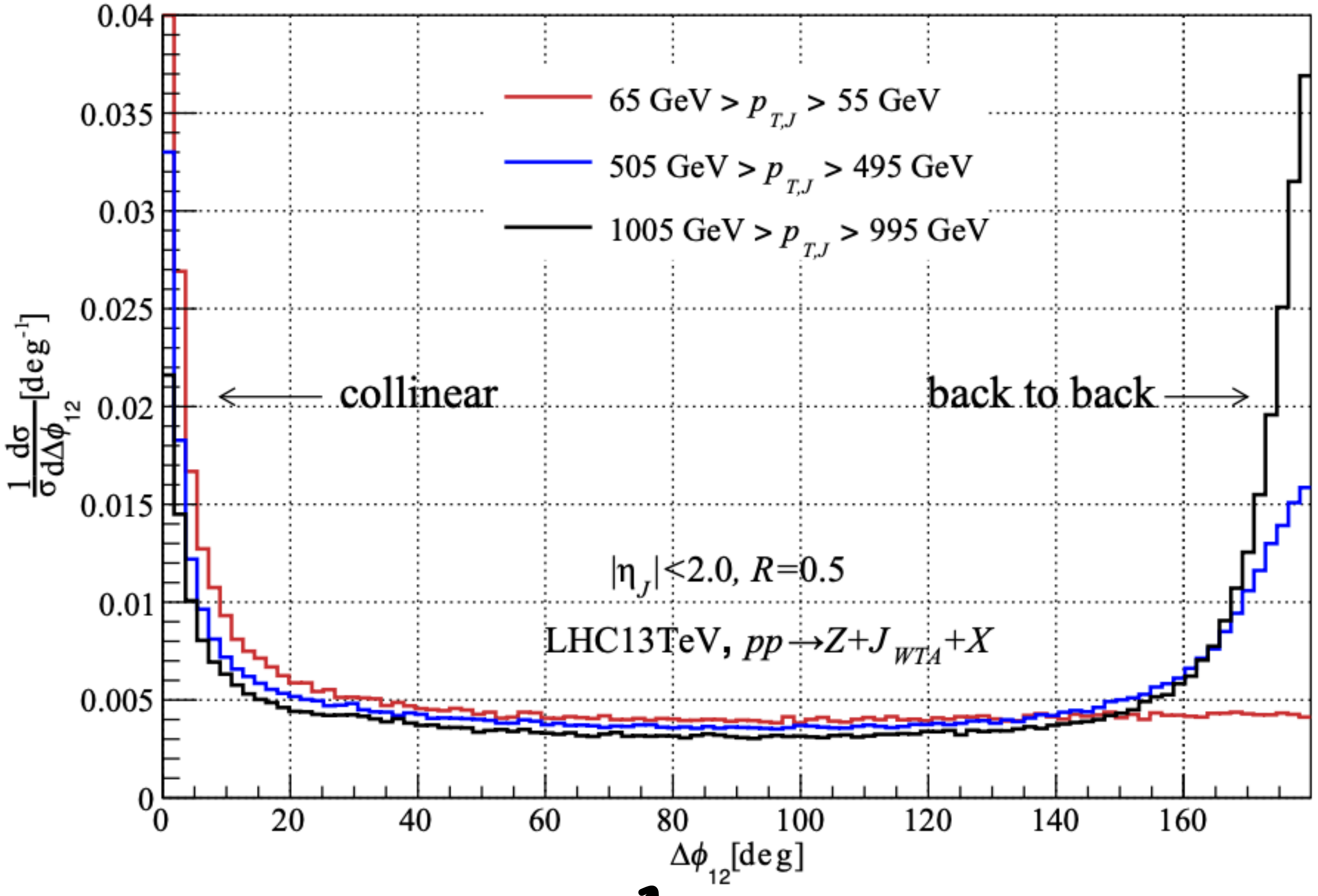




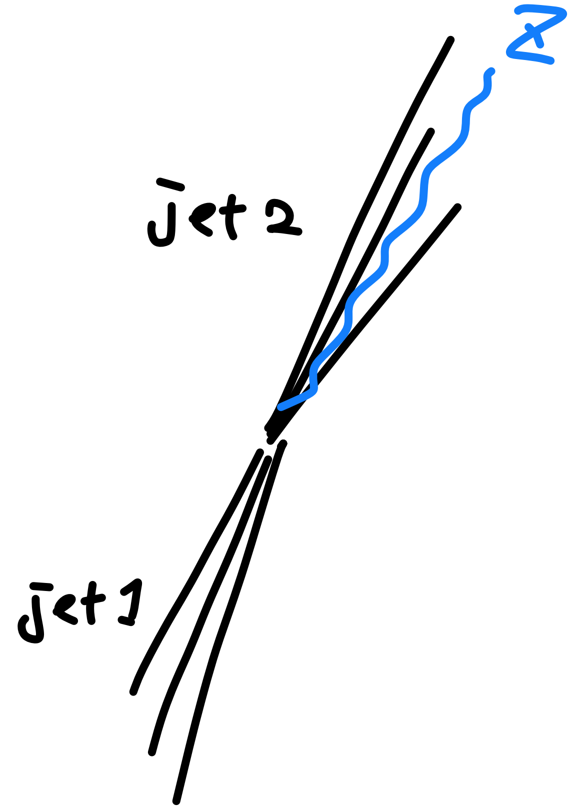
Large, nonsingular contribution not accounted for in Pythia

(Boson + dijet)

Boson+dijet phase space



angle between two partons in MCFM



At high energy, Z emitted off a jet starts to contribute significantly

* Included in MCFM

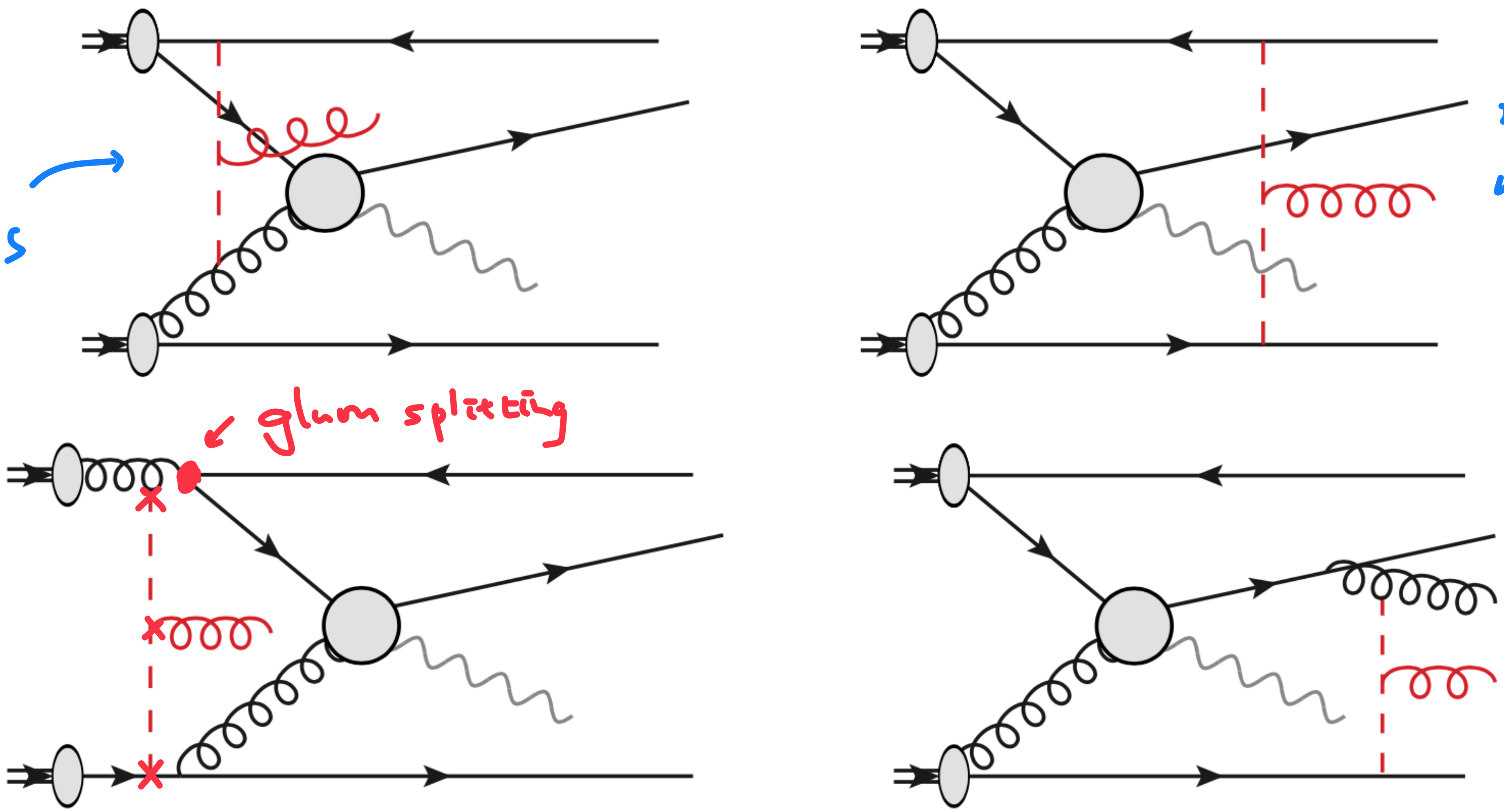
* not Included in Pythia (not yet look into it with EW shower)

Factorization breaking and Glauber

soft emission from Lipatov vertex

absorbed into soft Wilson lines

not contributing because beam remnant is not observed.



gluon splitting

Pure glauber exchanges do not break factorization

Factorization breaking may exist at $\mathcal{O}(\alpha_s^3)$

(we cannot prove an all-order statement)

Schwartz, Yan, Zhu
PRD 96 (2017) 056005
PRD 97 (2018) 096017

Summary

- Recoil-free definition of boson-jet angular decoorelation has the following advantages
  - Insensitive to hadronization, MPI
  - Minimum change when using charge tracks
  - No non global contribution with higher theory precision
- We provide NNLL matched to NLO theory prediction
  - NNNLL prediction possible in foreseeable future
- Factorization breaking effect may exist at $\mathcal{O}(\alpha_s^3)$

Outlook

- Recoil-free lepton-jet angular decorrelation at EIC is interesting to explore
- Recoil-free photon-jet (or dijet) angular decorrelation at RHIC is also interesting to explore
  - Polarized proton beams