Soft Gluon Rsummation for Dijet Production in pp Collisions

Reference:

Peng Sun, C.-P. Yuan, Feng Yuan, arXiv: 1405.1105; arXiv: 1506.06170

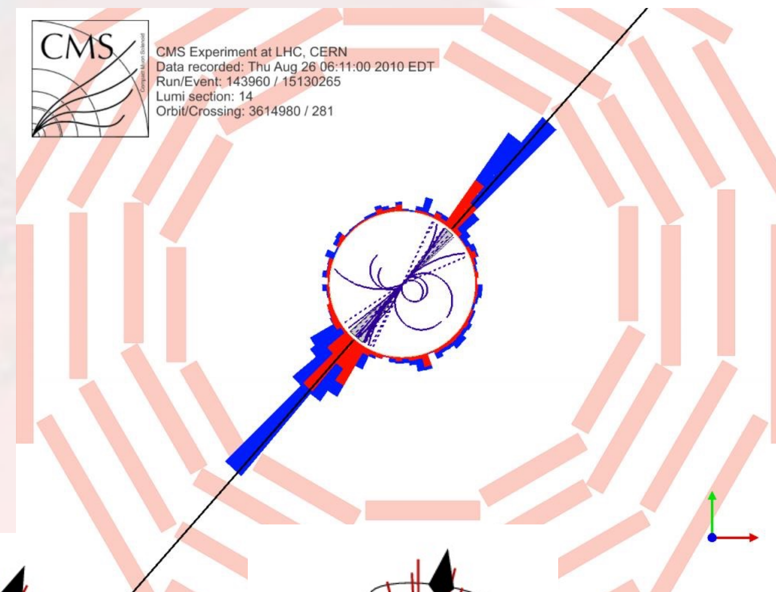
Hatta, Xiao, Yuan, Zhou, arXiv: 2010.10774; arXiv: 2106.05307

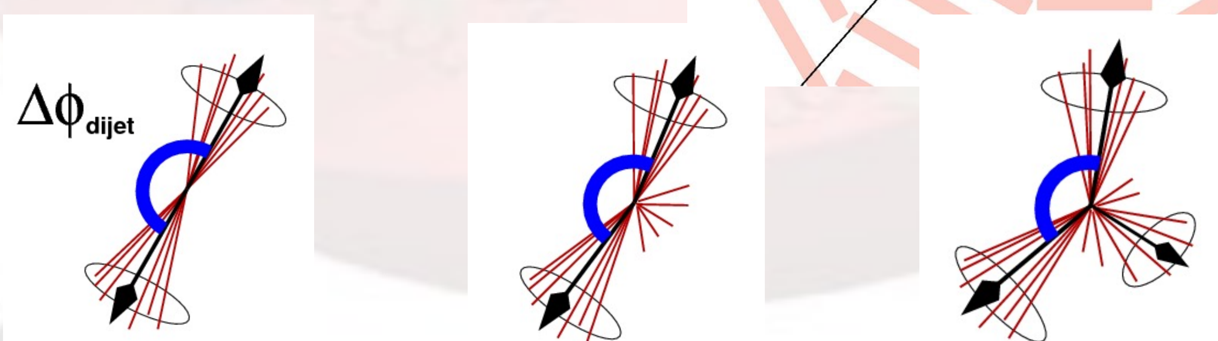
Outlines

- Experiments at Tevatron and LHC
- Soft gluon resummation in dijet production
  - Collins-Soper-Sterman
- Azimuthal angular asymmetry due to soft gluon radiation

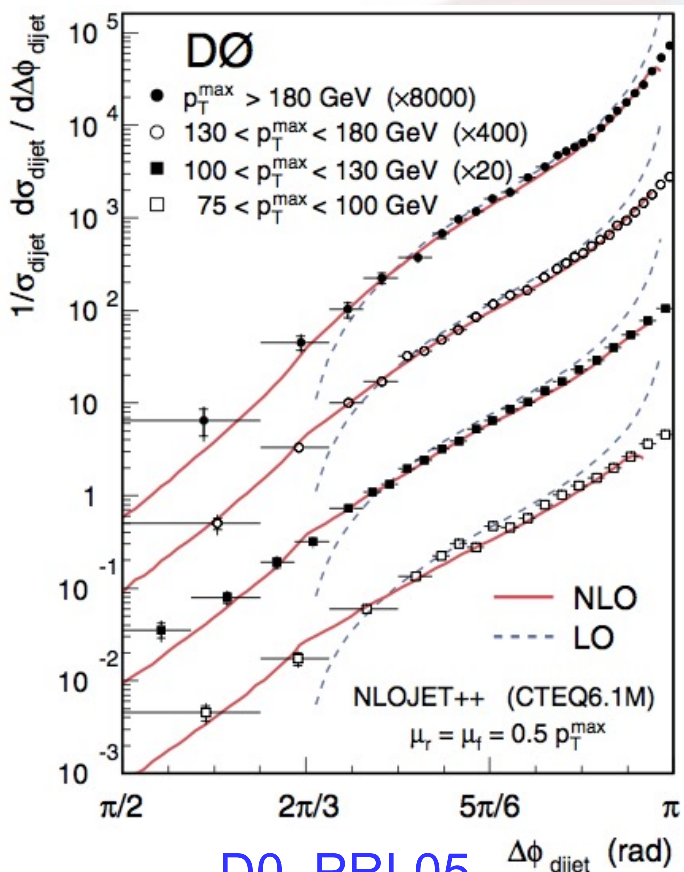
Dijet production at the hadron colliders

- Most abundant events
- Almost back-to-back
- De-correlation comes
  - Hard gluon jet
  - Soft gluon radiation

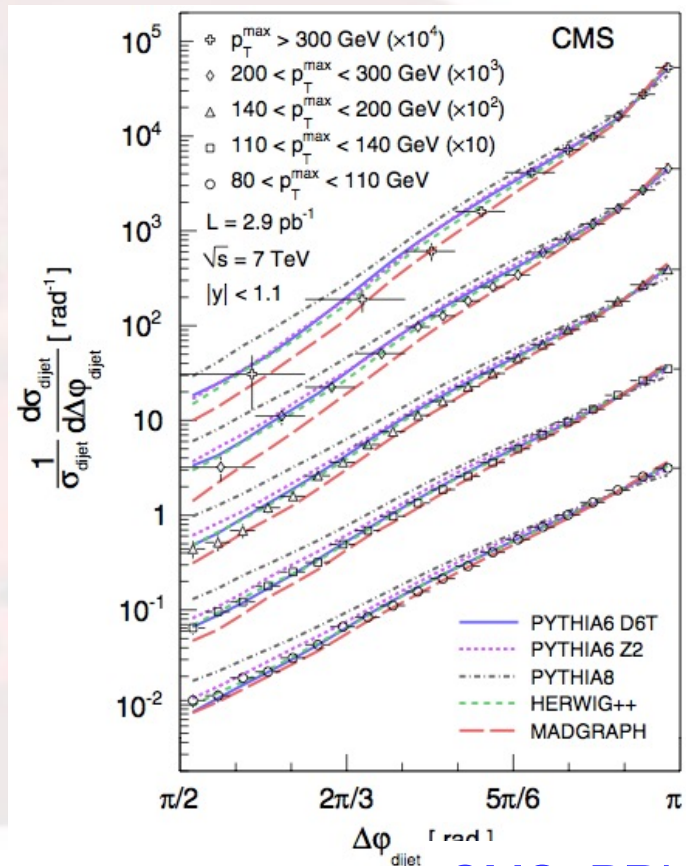




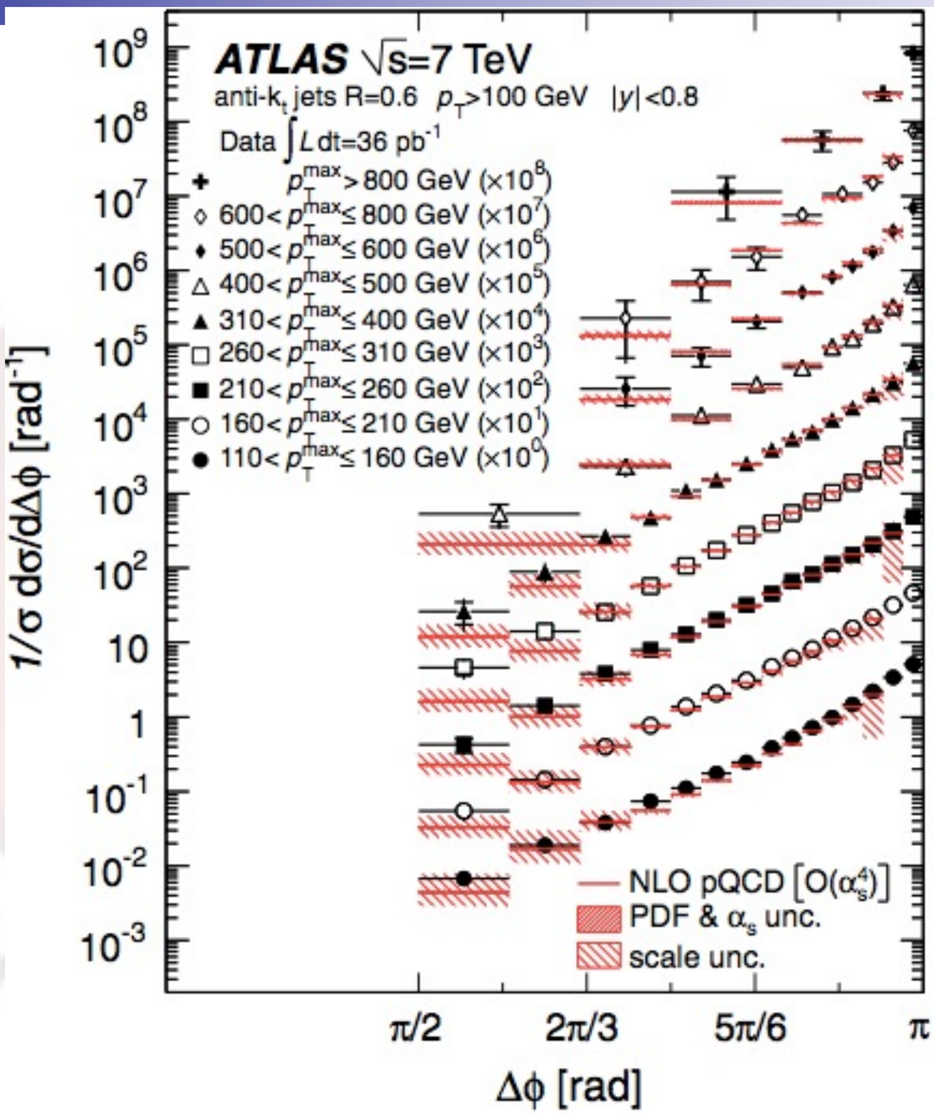
Beautiful data from Tevatron/LHC



D0, PRL05



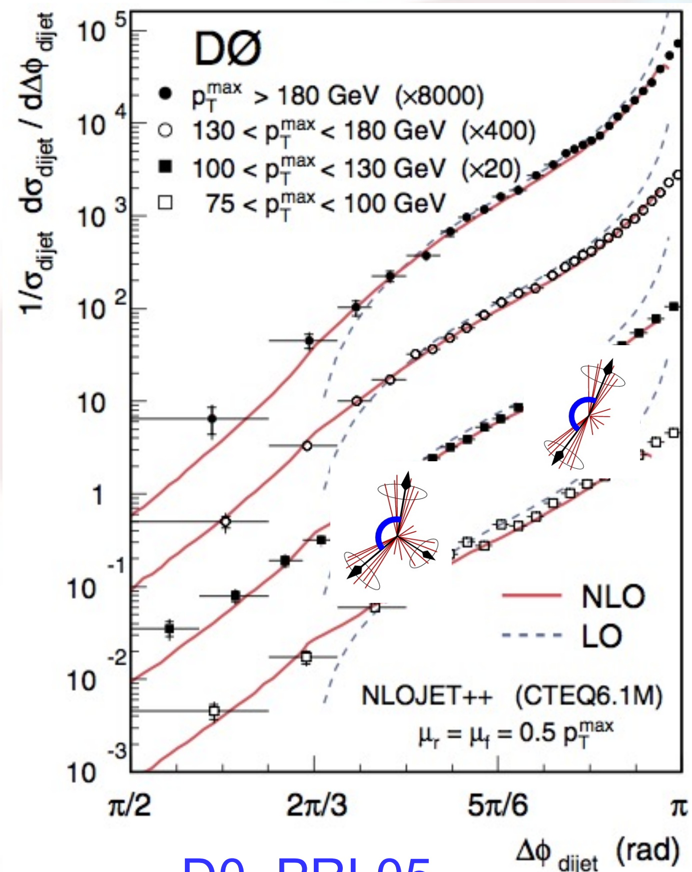
CMS, PRL11



ATLAS √s=7 TeV
anti-k_t jets R=0.6 p_T>100 GeV |y|<0.8
Data ∫L dt=36 pb^-1
p_T^max > 800 GeV (×10^8)
600< p_T^max ≤ 800 GeV (×10^7)
500< p_T^max ≤ 600 GeV (×10^6)
400< p_T^max ≤ 500 GeV (×10^5)
310< p_T^max ≤ 400 GeV (×10^4)
260< p_T^max ≤ 310 GeV (×10^3)
210< p_T^max ≤ 260 GeV (×10^2)
160< p_T^max ≤ 210 GeV (×10^1)
110< p_T^max ≤ 160 GeV (×10^0)
NLO pQCD [O(α_s^4)]
PDF & α_s unc.
scale unc.
1/σ dσ/dΔφ [rad^-1]
Δφ [rad]
π/2
2π/3
5π/6
π

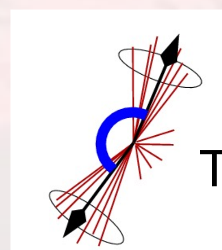
ATLAS, PRL11

QCD calculations



D0, PRL05

- Fixed order calculations divergent around π, where soft gluon radiation dominates
- All order resummation is needed to understand the physics around here
  - Two separate scales $P_T >> q_T$



Soft gluon radiation leads to Sudakov Logarithms

Sudakov, 1956; Collins-Soper-Sterman 1985

- Differential cross section depends on $Q_1=q_{T,}$ where $Q^2 >> Q_1^2 >> \Lambda^2_{QCD}$

$$\frac{d\sigma}{dQ_1^2} = \frac{1}{Q_1^2} f_1 \otimes f_2 \otimes \sum_i \alpha_s^i \ln^{2i-1} \frac{Q^2}{Q_1^2} + \cdots$$

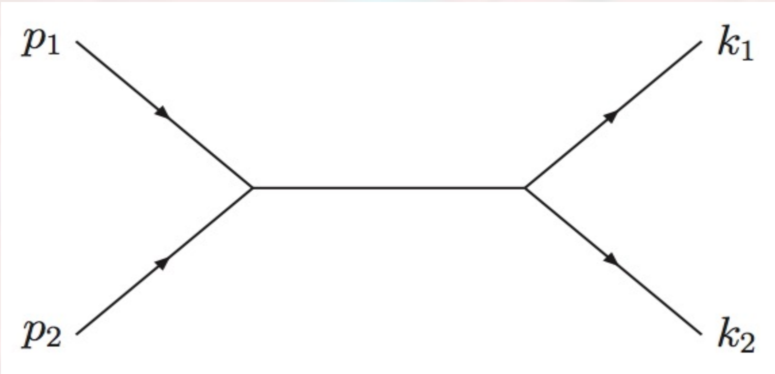
- Resummation of these large logs
  - In terms of transverse momentum dependent parton distributions and fragmentation functions and apply to
  - Semi-inclusive hadron production in DIS, Drell-Yan type of hard processes in pp collisions, e.g., Higgs, Z/W boson, …

Hard process with jet is different

- Final states carry color
  - Soft gluon radiation associated with the jet will contribute
  - Additional soft factor
- Jet algorithm will enter into the calculations as well
  - Only out of cone radiation contributes to the imbalance between the two jets

Leading double logs in dijet case

- Power counting: each incoming parton contributes to a half of the associated color factor



DL coefficient:
$A^{(1)}=(C_{p1}+C_{p2})/2$

Banfi-Dasgupta-Delenda, PLB 2008
Mueller-Xiao-Yuan, PRD 2013

Beyond the leading double logs

- Jet size-dependence is computed by averaging the azimuthal angle between the soft gluon and leading jet
- Matrix form due to colored final state   Kidonakis-Sterman 1997

$$x_1 f_a(x_1, \mu = b_0/b_\perp) x_2 f_b(x_2, \mu = b_0/b_\perp) e^{-S_{\rm Sud}(Q^2, b_\perp)}$$
$$\mathrm{Tr}\left[\mathbf{H}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu}\gamma^{s\dagger}] \mathbf{S}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu}\gamma^{s}]\right]$$

(Sun, C.-P. Yuan, F. Yuan, PRL 2014)

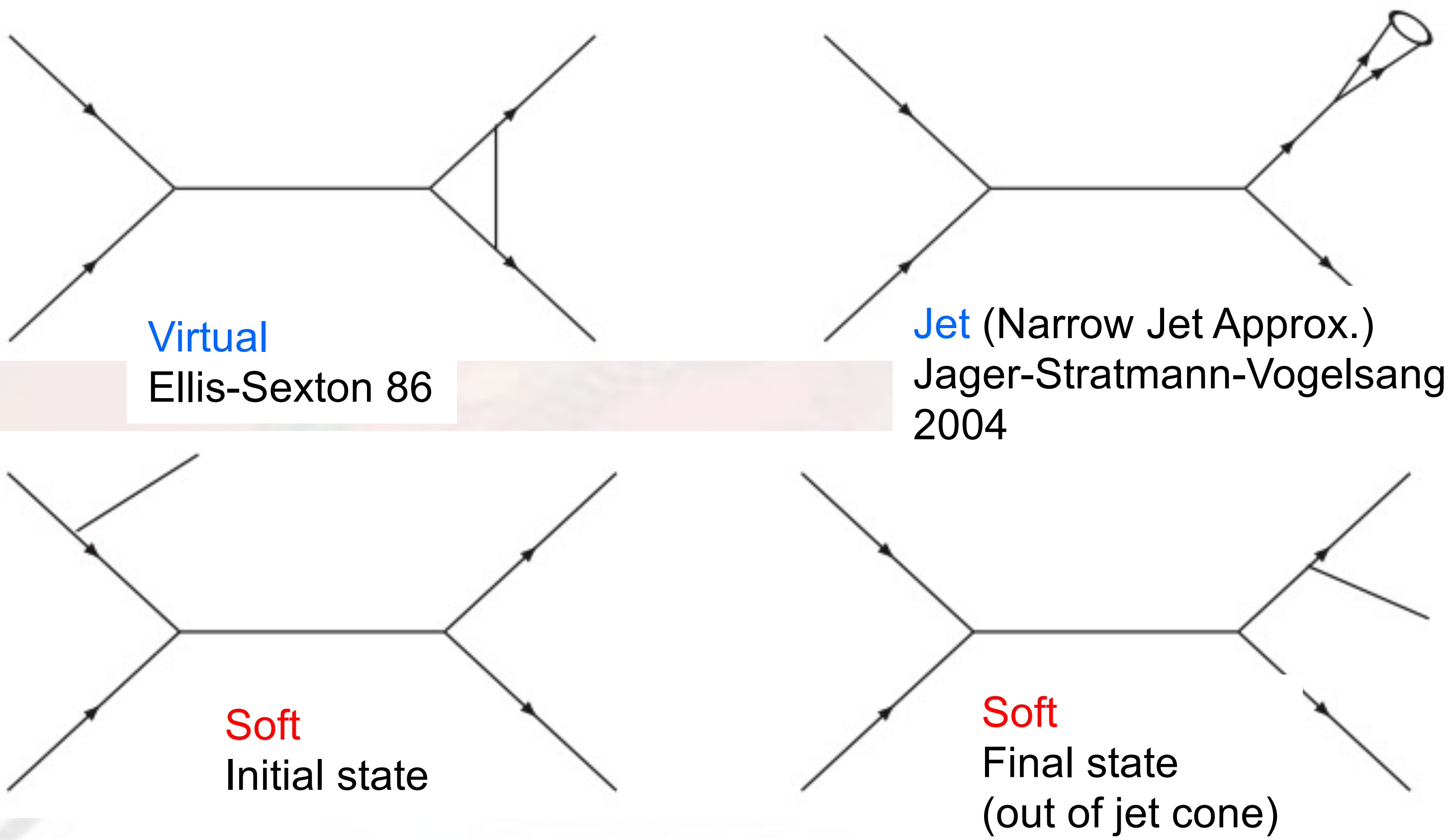
$$S_{\rm Sud}(Q^2, b_\perp) = \int_{b_0^2/b_\perp^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[\ln\left(\frac{Q^2}{\mu^2}\right) A + B + D_1 \ln\frac{Q^2}{P_T^2 R_1^2} + D_2 \ln\frac{Q^2}{P_T^2 R_2^2}\right]$$

D: color-factor for the jet

R: jet size

see also, heavy quark pair resummation:
Zhu-Li-Li-Shao-Yang 2012
Catani-Grazzini-Torre 2014

Soft and collinear gluon at one-loop



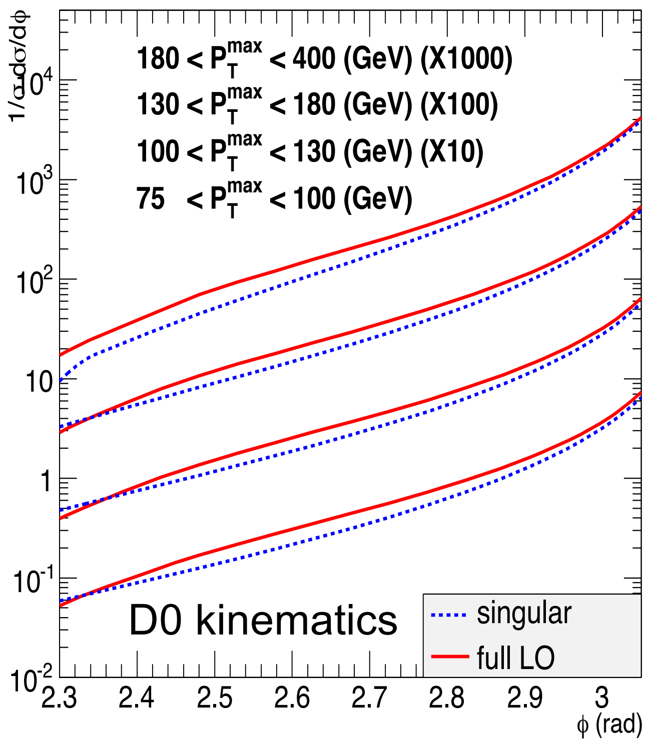
Cross checks

- Divergences cancelled out between virtual, jet, sot contributions (dimension regulation applied)
- Final results :double logs, single logs, ..

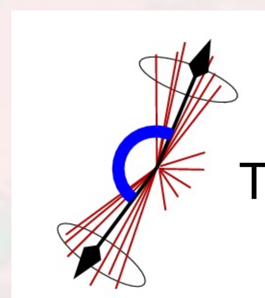
$$W^{(1)}(b_\perp)|_{logs.} = \frac{\alpha_s}{2\pi}\left\{h^{(0)}_{q_iq_j\to q_iq_j}\left[-\ln\left(\frac{\mu^2 b_\perp^2}{b_0^2}\right)\left(\mathcal{P}_{qq}(\xi)\delta(1-\xi') + \mathcal{P}_{qq}(\xi')\delta(1-\xi)\right) - \delta(1-\xi)\right.\right.$$
$$\left.\times\delta(1-\xi')\left(C_F\ln^2\left(\frac{Q^2b_\perp^2}{b_0^2}\right) + \ln\left(\frac{Q^2b_\perp^2}{b_0^2}\right)\left(-3C_F + C_F\ln\frac{1}{R_1^2} + C_F\ln\frac{1}{R_2^2}\right)\right)\right]$$
$$\left.-\delta(1-\xi)\delta(1-\xi')\ln\left(\frac{Q^2b_\perp^2}{b_0^2}\right)\Gamma^{(qq')}_{sn}\right\}, \quad (71)$$

Quark channel: $q_iq_j \to q_iq_j$

Compare to the full calculations



$$
\begin{aligned}
&\frac{\alpha_s}{2\pi^2}\frac{1}{q_\perp^2}\sum_{ab,a'b'}\sigma_0\int\frac{dx_1'}{x_1'}\frac{dx_2'}{x_2'}x_1' f_a(x_1',\mu)x_2' f_b(x_2',\mu)\\
&\times\Big\{h^{(0)}_{a'b'\to cd}\Big[\xi_1\mathcal{P}_{a'/a}(\xi_1)\delta(1-\xi_2)+\xi_2\mathcal{P}_{b'/b}(\xi_2)\delta(1-\xi_1)\\
&+\delta(1-\xi_1)\delta(1-\xi_2)\delta_{aa'}\delta_{bb'}\left((C_a+C_b)\ln\frac{Q^2}{q_\perp^2}+C_c\ln\frac{1}{R_1^2}+C_d\ln\frac{1}{R_2^2}\right)\Big]\\
&+\delta(1-\xi_1)\delta(1-\xi_2)\delta_{aa'}\delta_{bb'}\Gamma_{sn}^{ab\to cd}\Big\}\ , \qquad (10
\end{aligned}
$$

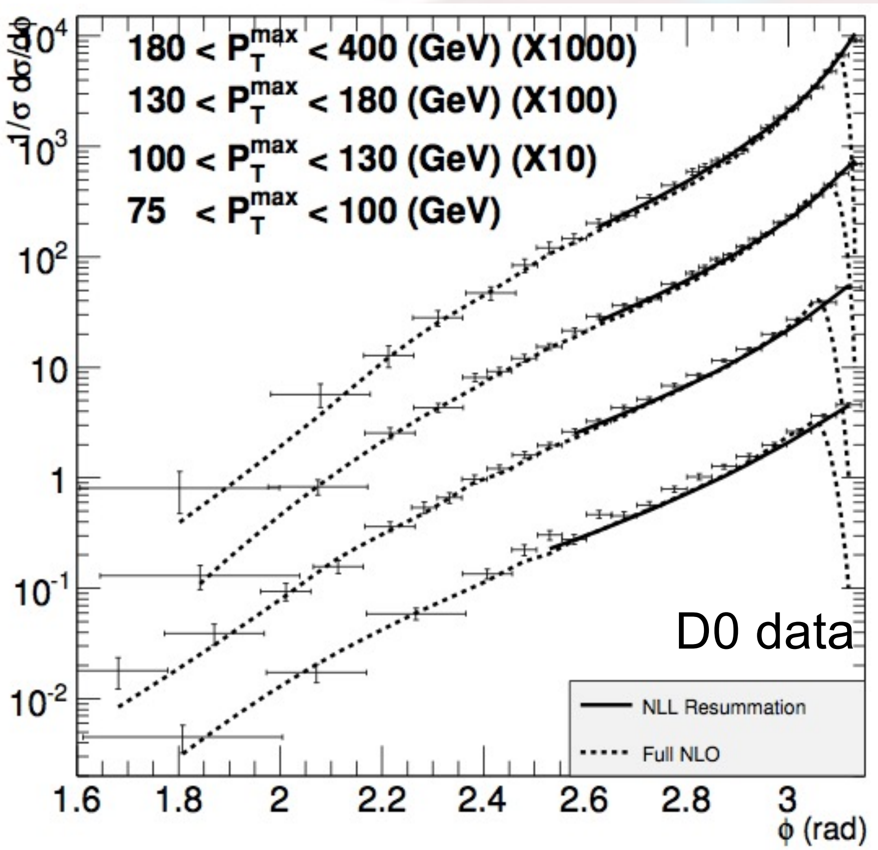


Leading P_T

Total $q_T \approx P_T \mathrm{Sin}(\Delta\phi)$

full LO: Nagy 2002, NLOJET++

Compare to the data

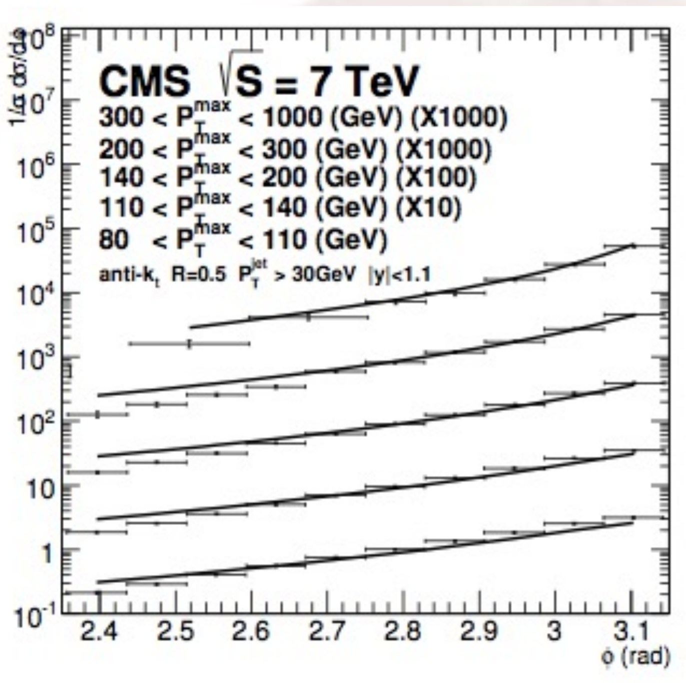


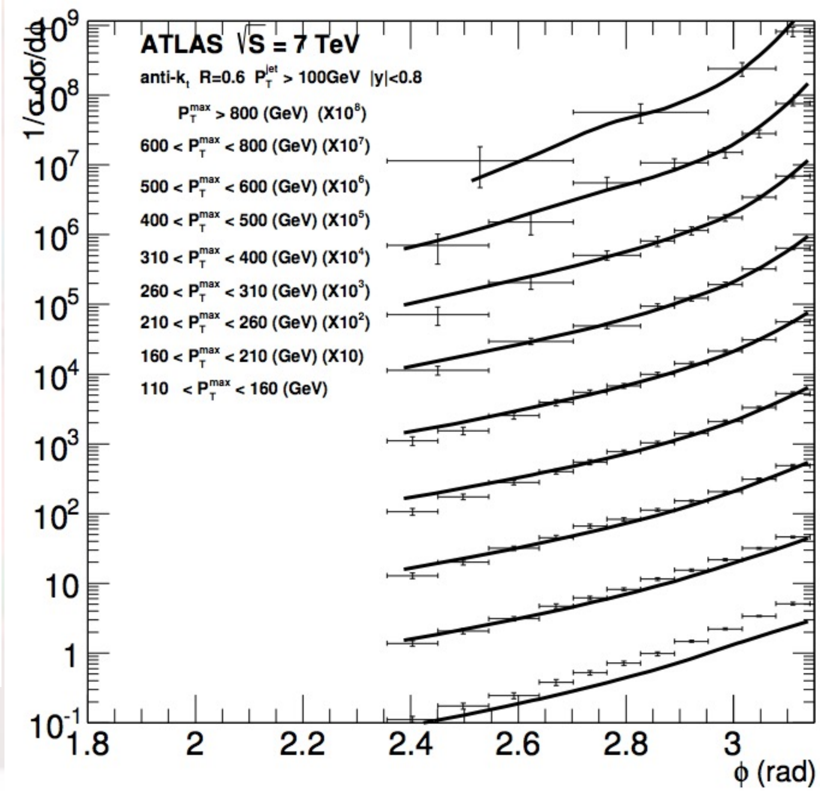
NLL Resummation:
Sun,C.P.Yuan, F.Yuan, PRL2014

$$x_1 f_a(x_1, \mu = b_0/b_\perp) x_2 f_b(x_2, \mu = b_0/b_\perp) e^{-S_{\rm Sud}(Q^2, b_\perp)}$$
$$\mathrm{Tr}\left[\mathbf{H}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu}\gamma^{s\dagger}] \mathbf{S}_{ab\to cd} \exp[-\int_{b_0/b_\perp}^{Q} \frac{d\mu}{\mu}\gamma^{s}]\right]$$

Full NLO: Nagy 2002, NLOJET++

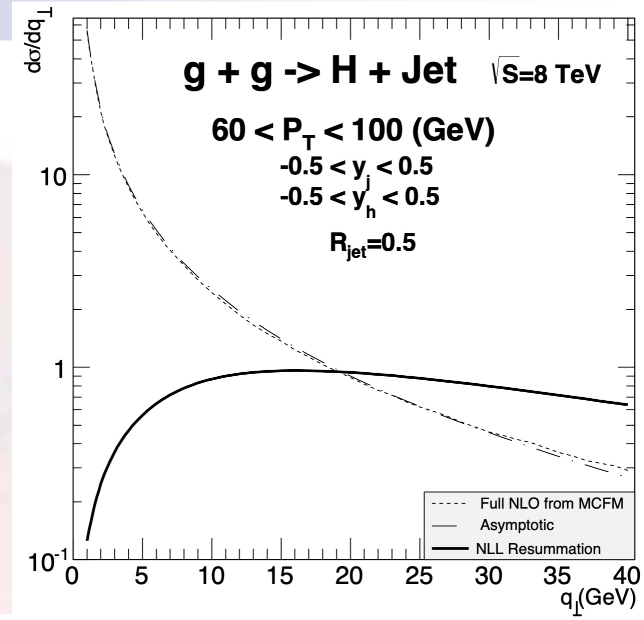
At the LHC

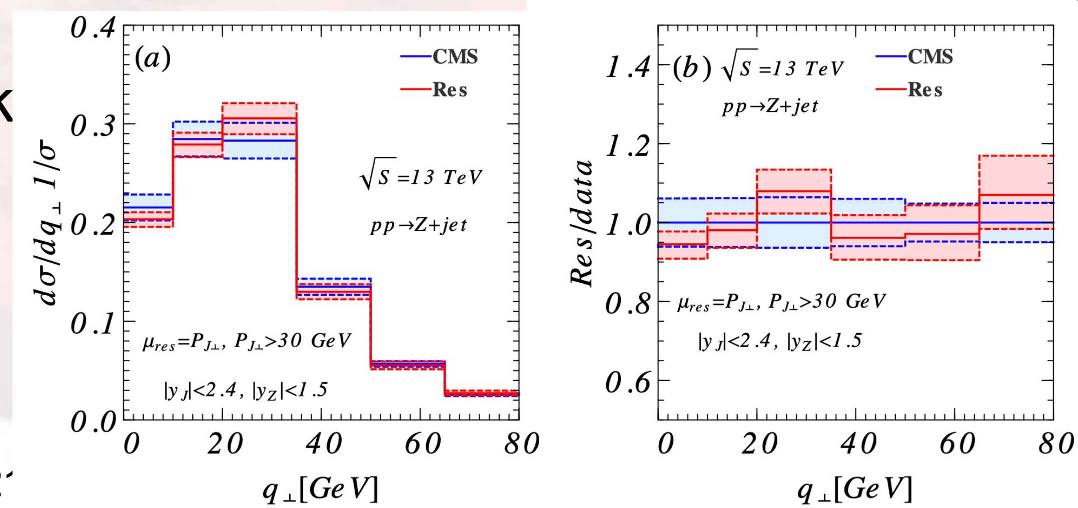

CMS √S = 7 TeV
300 < P_T^max < 1000 (GeV) (X1000)
200 < P_T^max < 300 (GeV) (X1000)
140 < P_T^max < 200 (GeV) (X100)
110 < P_T^max < 140 (GeV) (X10)
80 < P_T^max < 110 (GeV)
anti-k_t R=0.5 P_T^jet > 30GeV |y|<1.1
1/σ dσ/dφ
φ (rad)


ATLAS √S = 7 TeV
anti-k_t R=0.6 P_T^jet > 100GeV |y|<0.8
P_T^max > 800 (GeV) (X10^8)
600 < P_T^max < 800 (GeV) (X10^7)
500 < P_T^max < 600 (GeV) (X10^6)
400 < P_T^max < 500 (GeV) (X10^5)
310 < P_T^max < 400 (GeV) (X10^4)
260 < P_T^max < 310 (GeV) (X10^3)
210 < P_T^max < 260 (GeV) (X10^2)
160 < P_T^max < 210 (GeV) (X10)
110 < P_T^max < 160 (GeV)
1/σ dσ/dφ
φ (rad)

More simpler processes

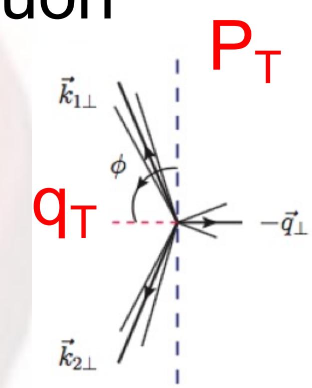
- Higgs+Jet
  - Sun,C.P.Yuan,F.Yuan, 1409.4121
- Z(photon)+Jet
  - Sun,Yan, C.P.Yuan,F.Yuan, 1810.03804
- Dijet in DIS
  - Rafael and Farid's talk
- Lepton+Jet
  - Arratia's talk





Azimuthal angular asymmetries

Catani-Grazzini-Sargsyan 2017



- Azimuthal angular asymmetries arise from soft gluon radiations
  - ϕ is defined as angle between total and different transverse momenta of the two final state particles
- Infrared safe but divergent
  - $\langle\cos(\phi)\rangle$, $\langle\cos(2\phi)\rangle$, … divergent, $\sim 1/q_T^2$
  - Integral is finite for small q_T-cutoff, resummation can be carried out for the harmonics, $\langle\cos(n\phi)\rangle \sim q_T^n$
  - Examples discussed include Vj, top quark pair production

Azimuthal angular correlations in jet production processes

Hatta, Xiao, Yuan, Zhou, arXiv: 2010.10774; 2106.05307

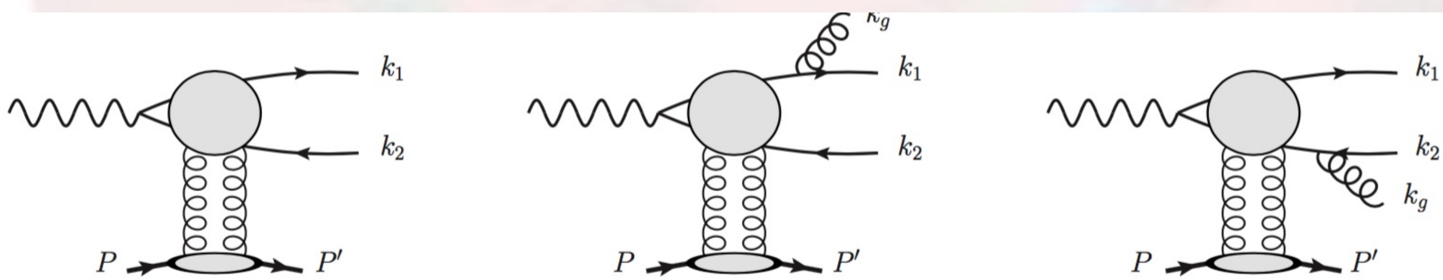
- Diffractive photoproduction of dijet
- Lepton plus jet production at the EIC
- Inclusive dijet in DIS

Example: Diffractive dijet production

- Gluon radiation tends to be aligned with the jet direction

$$S_J(q_\perp) = \delta(q_\perp) + \frac{\alpha_s}{2\pi^2}\int dy_g \left(\frac{k_1\cdot k_2}{k_1\cdot k_g k_2\cdot k_g}\right)_{\vec{q}_\perp=-\vec{k}_{g\perp}}$$

$$S_{J0}(|q_\perp|) + 2\cos(2\phi)S_{J2}(|q_\perp|) + \cdots$$



Hatta-Xiao-Yuan-Zhou, 2010.10774
anisotropy was neglected in an earlier paper: Hatta-Mueller-Ueda-Yuan, 1907.09491

Leading power contributions, explicit result at α_s

$$S_J(q_\perp) = S_{J0}(|q_\perp|) + 2\cos(2\phi) S_{J2}(|q_\perp|)$$

$$S_{J0}(q_\perp) = \delta(q_\perp) + \frac{\alpha_0}{\pi}\frac{1}{q_\perp^2}\,, \quad S_{J2}(q_\perp) = \frac{\alpha_2}{\pi}\frac{1}{q_\perp^2}\,,$$

where

$$\alpha_0 = \frac{\alpha_s C_F}{2\pi} 2\ln\frac{a_0}{R^2}\,, \quad \alpha_2 = \frac{\alpha_s C_F}{2\pi} 2\ln\frac{a_2}{R^2}\,.$$

a_0,a_2 are order 1 constants, so,

in the small-R limit, <cos(2ϕ)> goes to 1

Leading logarithmic resummation

$$\widetilde{S}_{J0}(b_\perp) = e^{-\Gamma_0(b_\perp)}\ ,\quad \widetilde{S}_{J2}(b_\perp) = \alpha_2 e^{-\Gamma_0(b_\perp)}\qquad \Gamma_0(b_\perp) = \int_{\mu_b^2}^{P_\perp^2} \frac{d\mu^2}{\mu^2}\alpha_0$$

EIC

Kinematics:

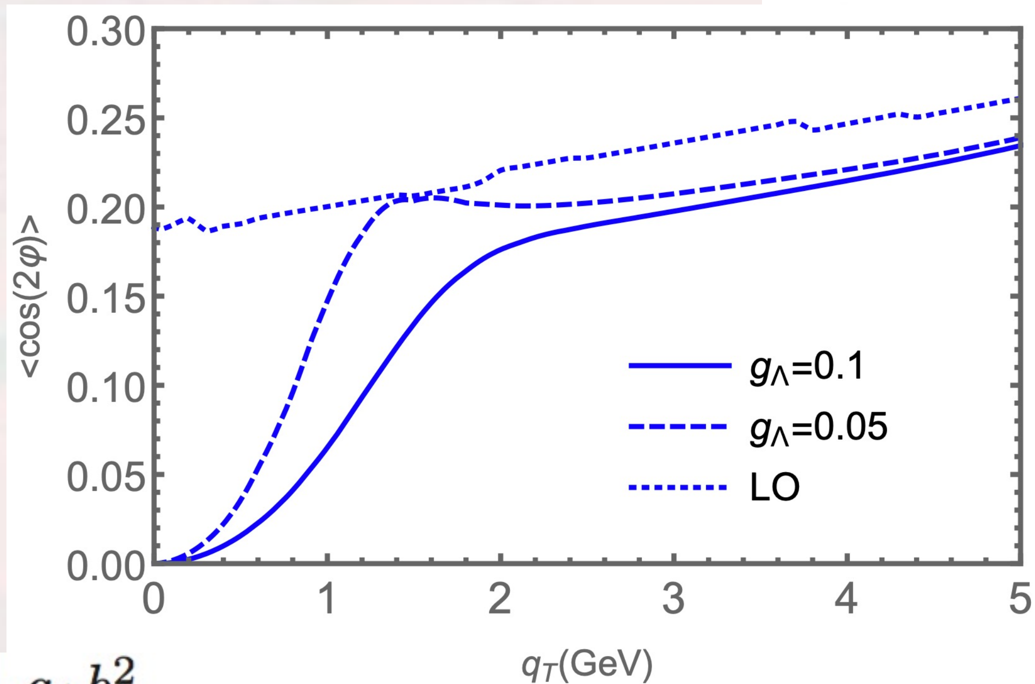
P_T~15GeV

R=0.4

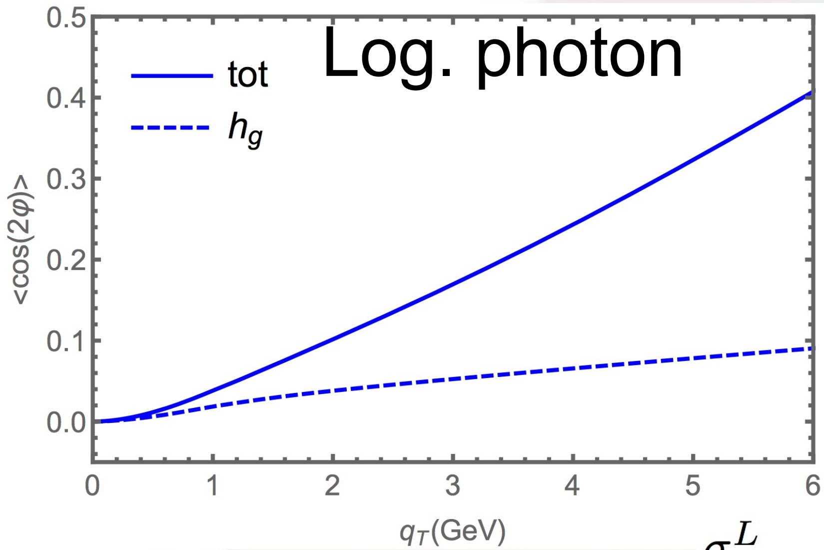
$y_1=y_2$

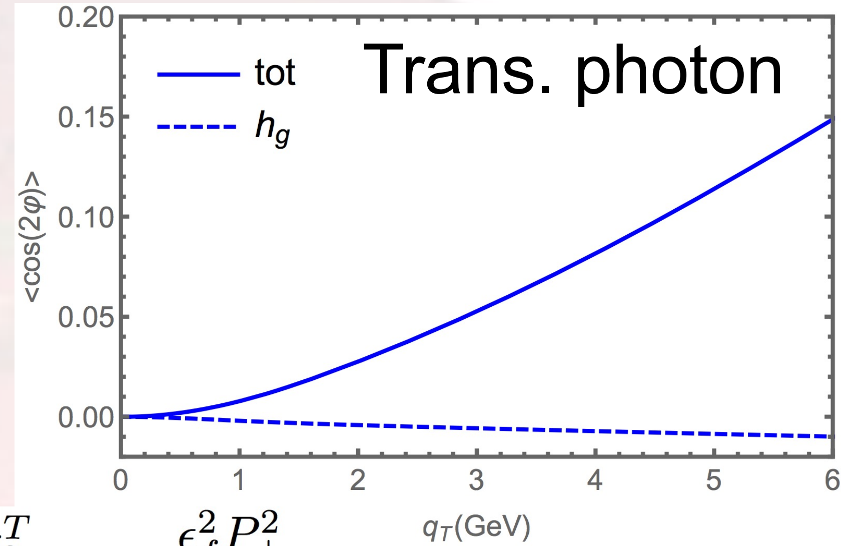
Non-pert. input:

$$\Gamma_0(b_\perp) \Longrightarrow \Gamma_0(b_*) + g_\Lambda b_\perp^2$$



Inclusive dijet at EIC: Q=10GeV, P_T=15GeV, R=0.4





$$\frac{\sigma_2^L}{\sigma_0^L} = \frac{1}{2} \qquad \frac{\sigma_2^T}{\sigma_0^T} = -\frac{\epsilon_f^2 P_\perp^2}{\epsilon_f^4 + P_\perp^4}$$

- The difference between the above two purely comes from the linearly polarized gluon distribution

Summary

- Soft gluon resummation is needed to describe the dijet correlation from Tevatron/LHC
- Soft gluon radiation contributes to azimuthal angular asymmetry as well
  - LLA resummation derived
  - More sophistic approach, see talk by Jürg Haag (Tue)
- Implement all these in a parton shower?
  - See previous talk