Precision Jet Physics At the LHC

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OUTLINE

- Introduction
  - Why are jets interesting?
  - How should we **study** them?

e.g. SCET

- Start **simple**
  - Two jets in e^+e^-

e.g. EVENT SHAPES

- Add **complexity**
  - Two protons + one jet

e.g. DIRECT PHOTON

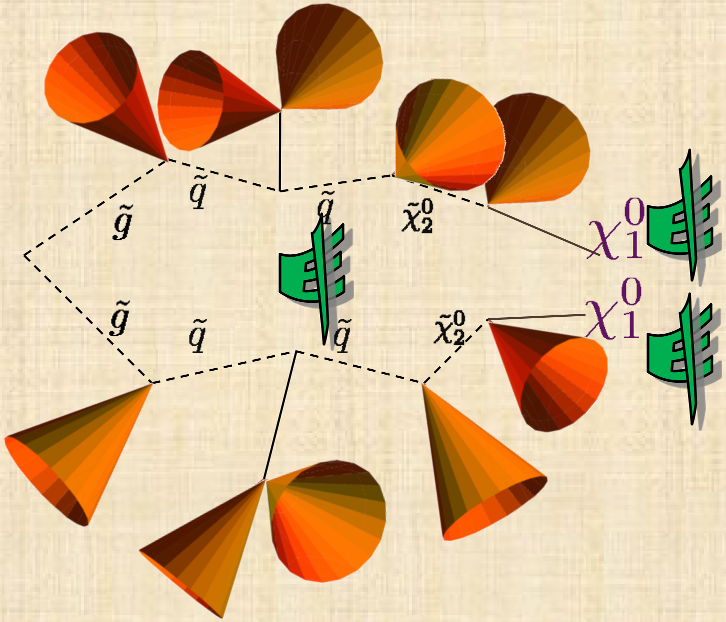
- Getting **close** to multijets
  - Enormous cross section
  - Tests QCD, find new physics

e.g.. DIJETs

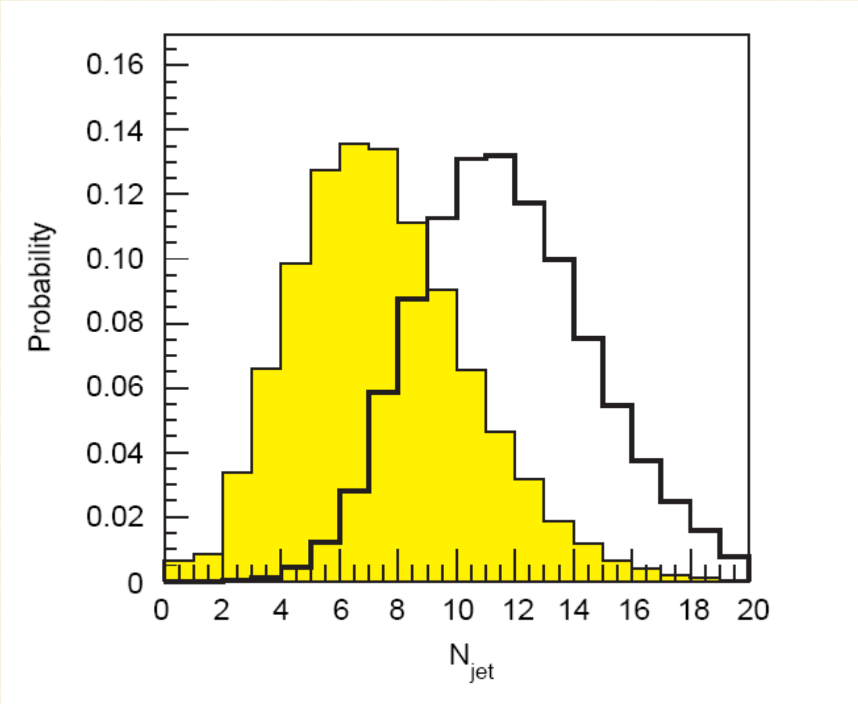
- Conclusions

JETS AT THE LHC

An (almost) universal feature of SUSY is ***jets*** and **missing energy**

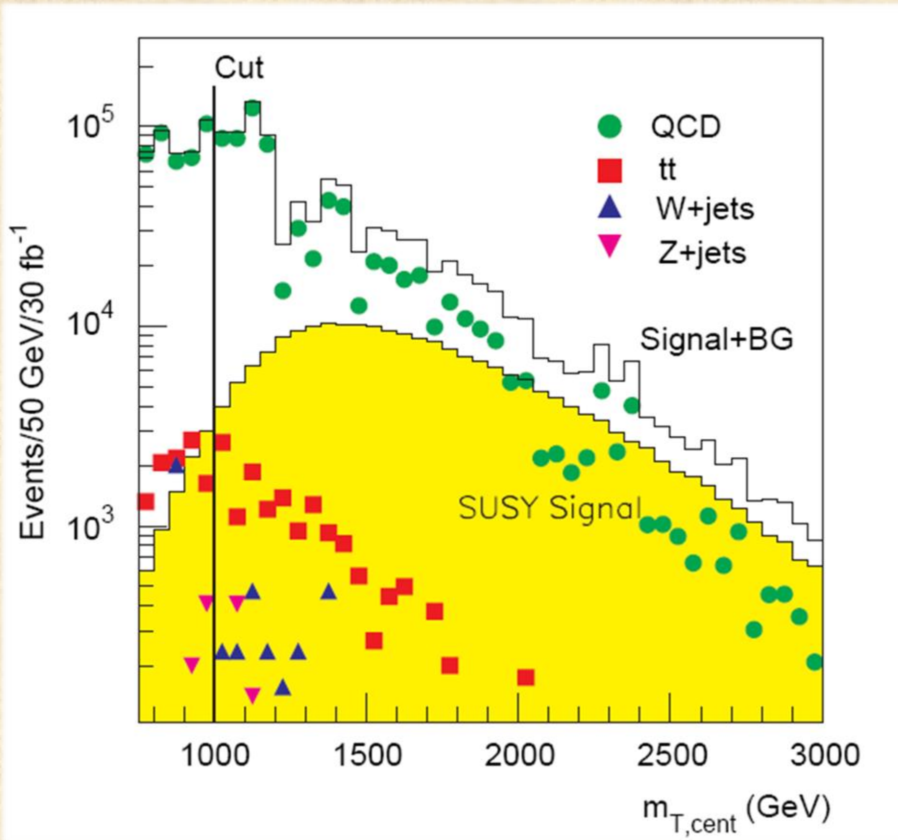


Source: Atlas TDR



SIGNAL VS. BACKGROUND

Source: Atlas TDR



How do we **know** what the background is?

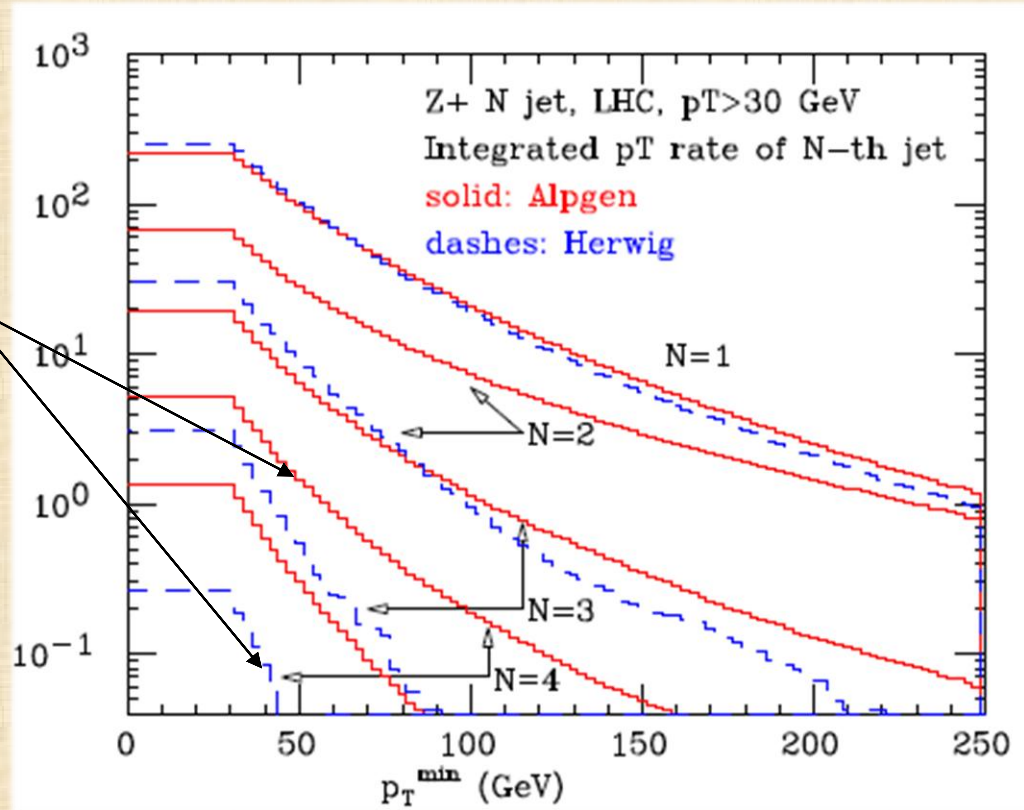
Can we **trust** our estimates?

CAN WE TRUST THE BACKGROUNDS?

Compare two monte carlos: Alpgen and Herwig

Source: M. Mangano

- Factor of 10 ~ 100 already at 4 jets – we need 8-12.
- What is the right answer?



WHAT IS THE RIGHT ANSWER?

- Ask the **data**

  calibrate detectors

  tune Monte Carlos

  measure PDFs

  find new physics

  All at the same time…

- Ask **Madgraph/Alpgen**
  - Includes any 2→n matrix element at tree level

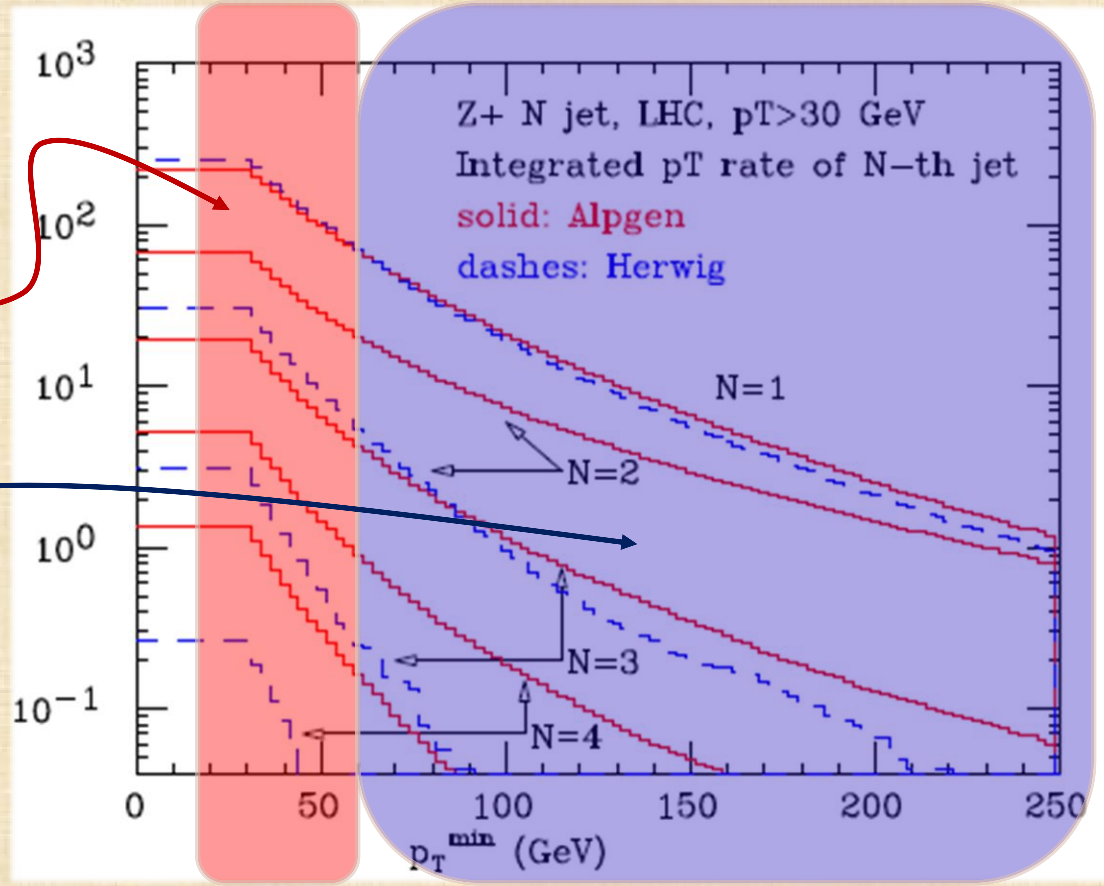
- Ask **MC@NLO/Powheg/Rocket/Blackhat**
  - 1-loop matrix elements

- Ask **PYTHIA**
  - Only includes 2→2 (some 2→3) tree-level matrix elements
  - Includes Leading Log resummation

HOW IMPORTANT IS RESUMMATION?

Improvements here

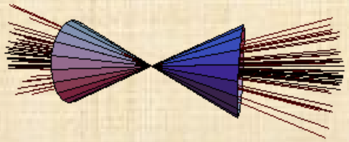
Madgraph, Alpgen, MC@NLO, Powheg, Rocket, Blackhat



What about **the rest**?
Can we go beyond **PYTHIA (LL resummation)**?

WHY RESUMMATION?

- Fixed order QCD has large Logarithms



m = mass of jet
E = energy of jet

$d\sigma = 1 - \alpha \log (m/E)$

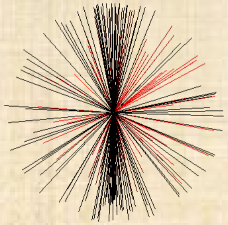
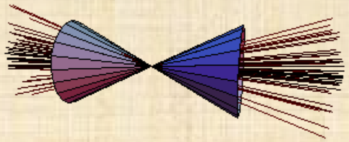
- We want to **resum the large logarithms**

$d\sigma = \exp[-\alpha \log (m/E)]$ $\quad m << E$

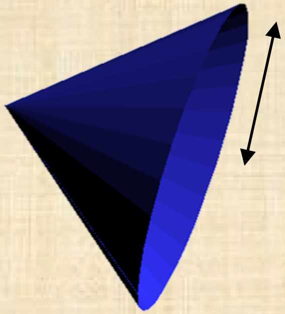
- Can this be done by separating out the **physical scales** and using the **renormalization group**?

Yes! With **Effective Field Theory**!

SOFT-COLLINEAR EFFECTIVE THEORY

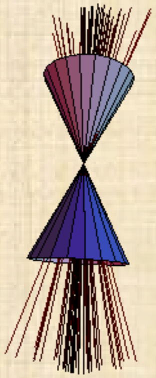
SCET interpolates between fat jets  and thin jets 

By expanding in the transverse size of the jet

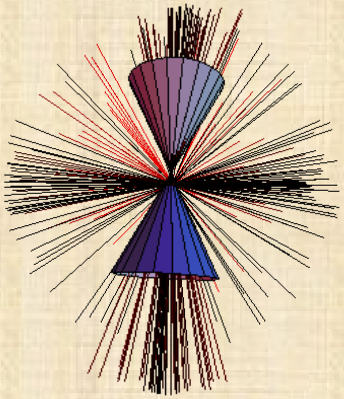


$\mu \sim \mathbf{k_t} \sim (\mathbf{mE})^{½}$

We will start simple and head towards the LHC

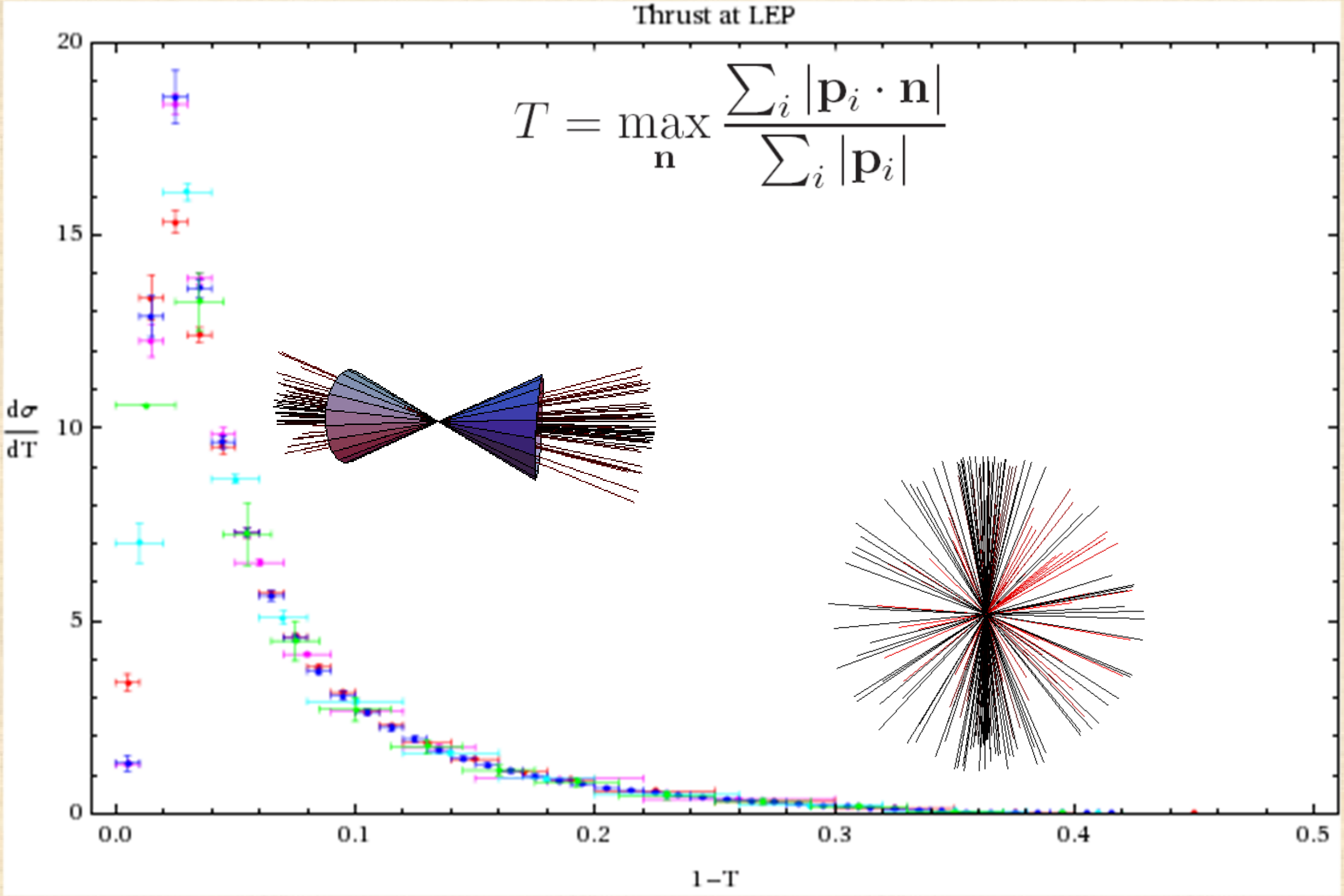


$e^+e^- \rightarrow$ jets



$p^+p^+ \rightarrow$ jets

e^+e^- EVENT SHAPES



Thrust provides some of the best data in the world

1 million clean events from LEP

Measurements of α_s have been ***theory limited!***

THRUST WITH SCET

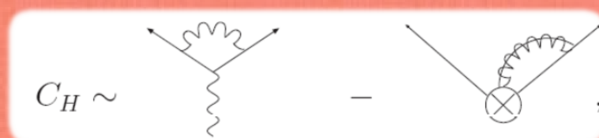
Fleming, Hoang, Mantry, Stewart (hep-ph/0703207)

MDS, PRD:77.14026 (2008)

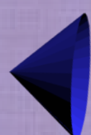
For the thrust distribution:

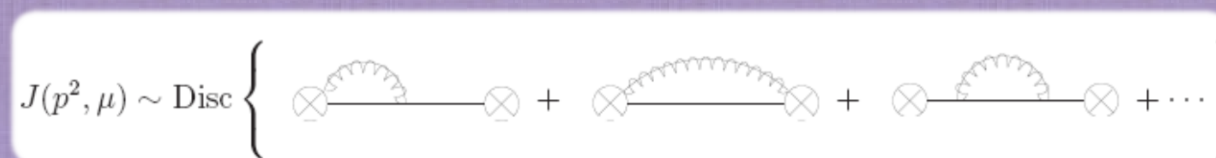
$$\frac{1}{\sigma_0}\frac{d^2\sigma}{d\tau} = |C_H(Q)|^2 \int dp^2\, dq^2\, J(p^2)\, J(q^2)\, S_T\left(\tau Q - \frac{p^2+q^2}{Q}\right)$$

Hard Function:

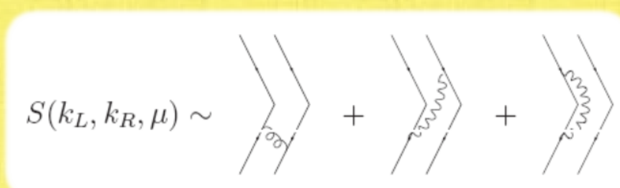


Jet Function:

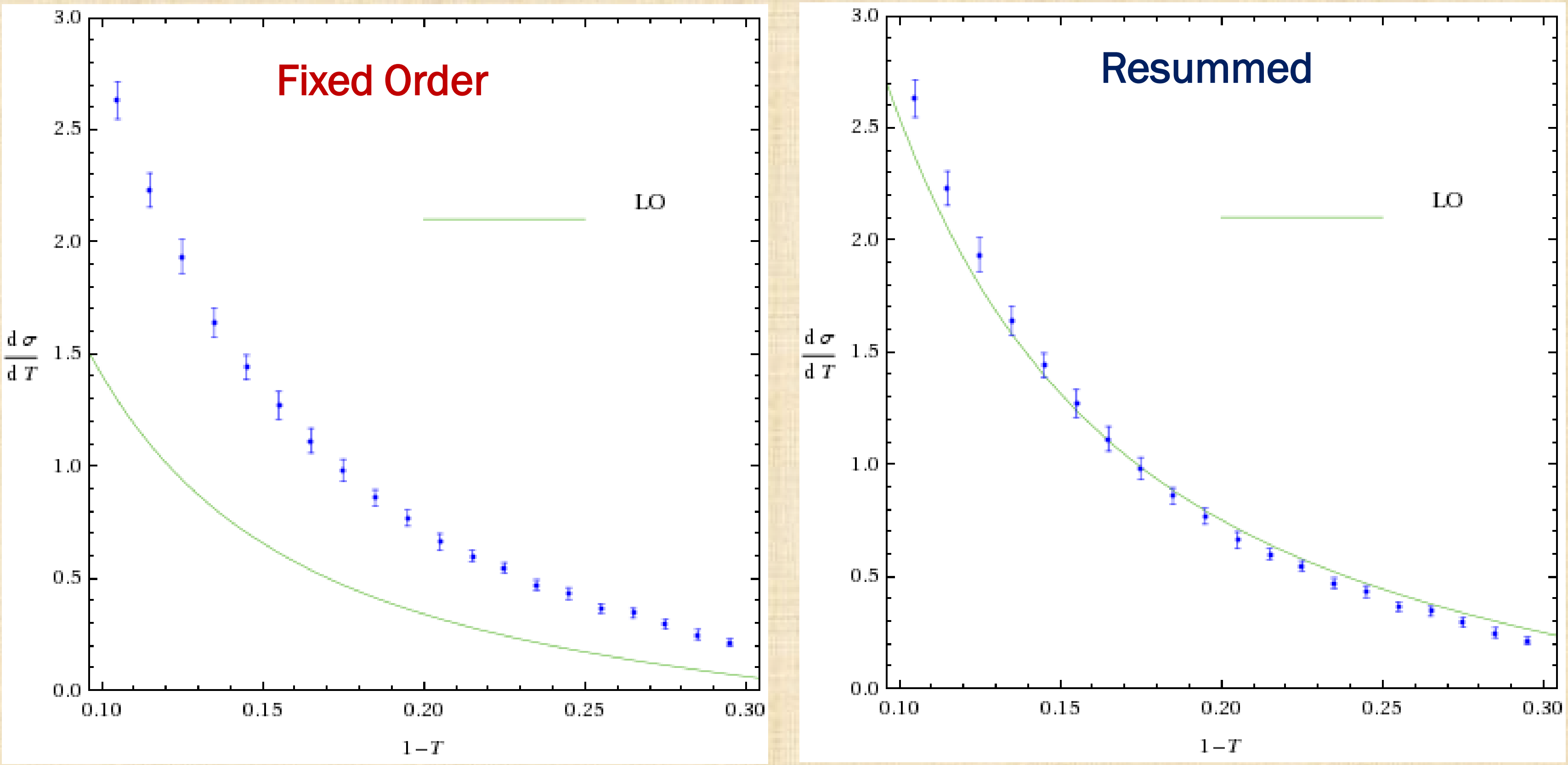




Soft Function:

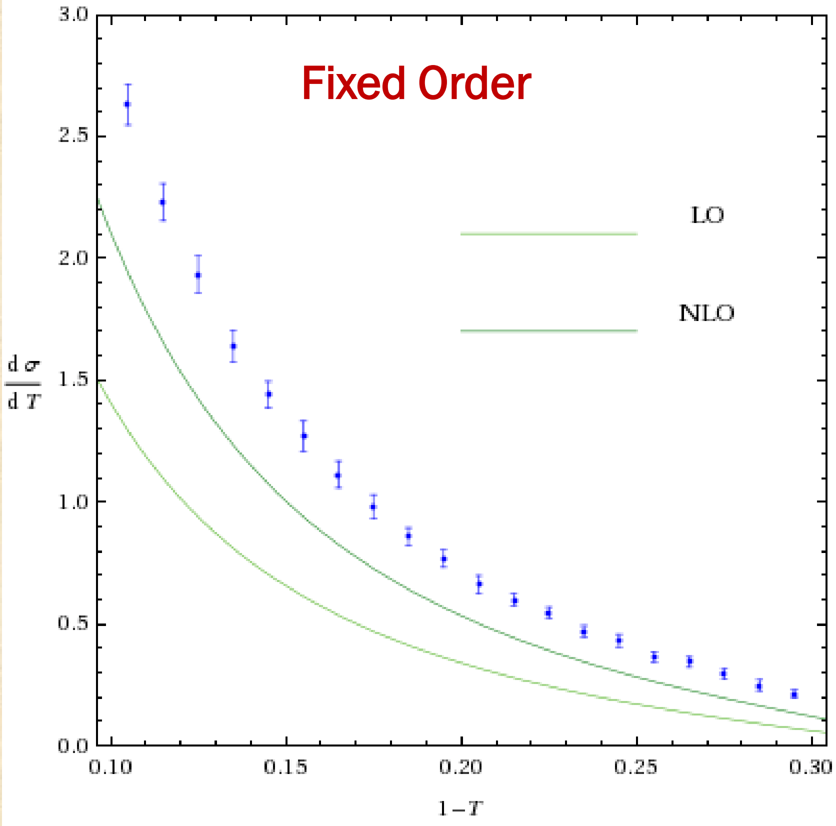


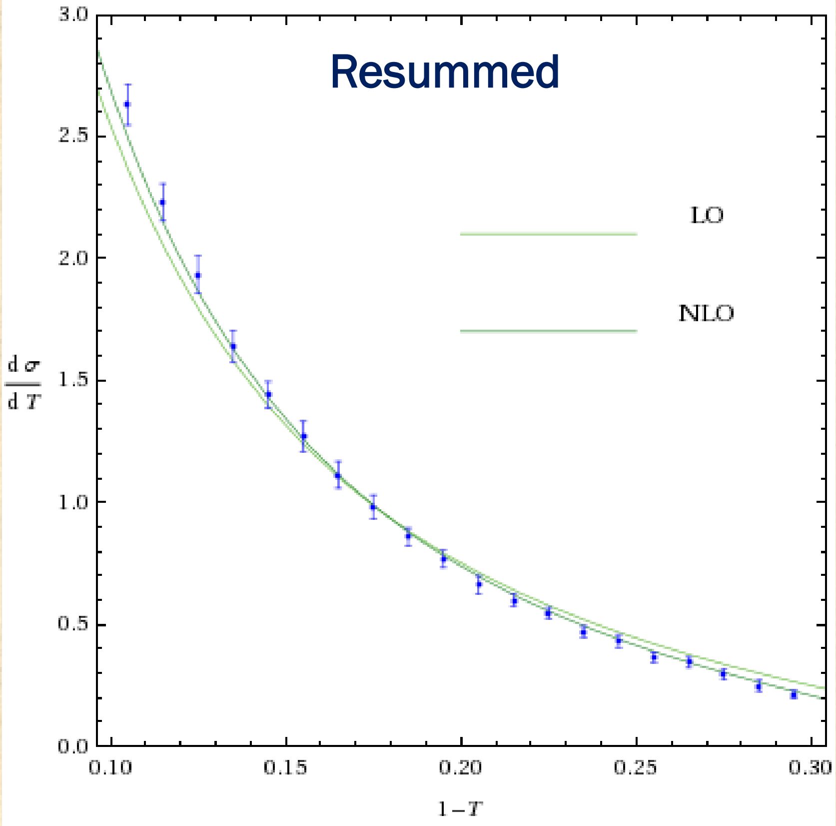
CONVERGENCE



At fixed $\alpha_s(M_Z) = 0.1168$

CONVERGENCE





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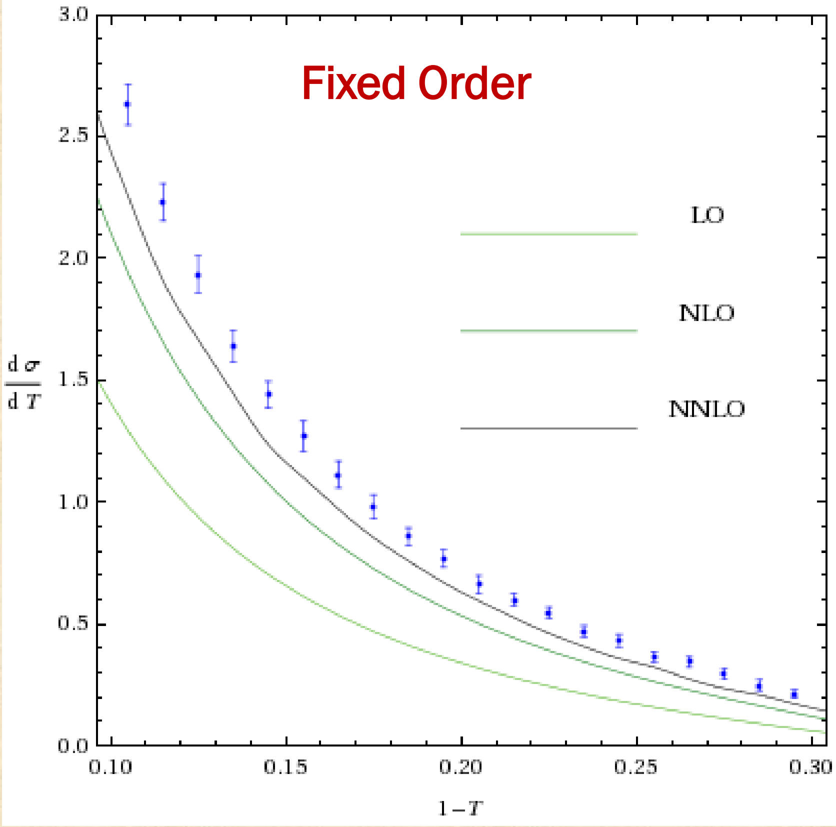
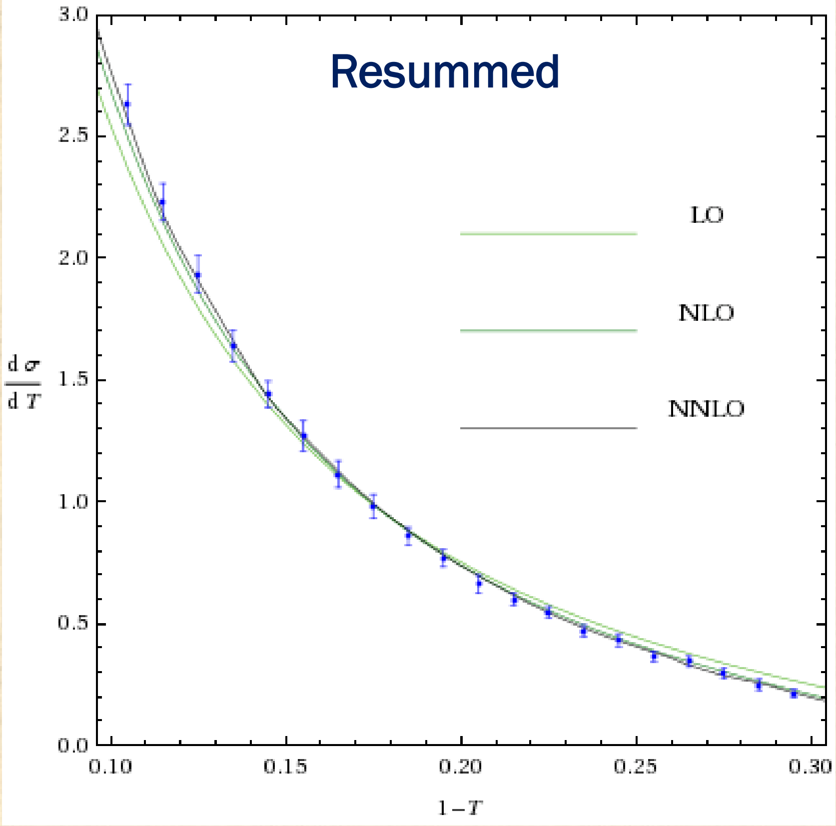
CONVERGENCE

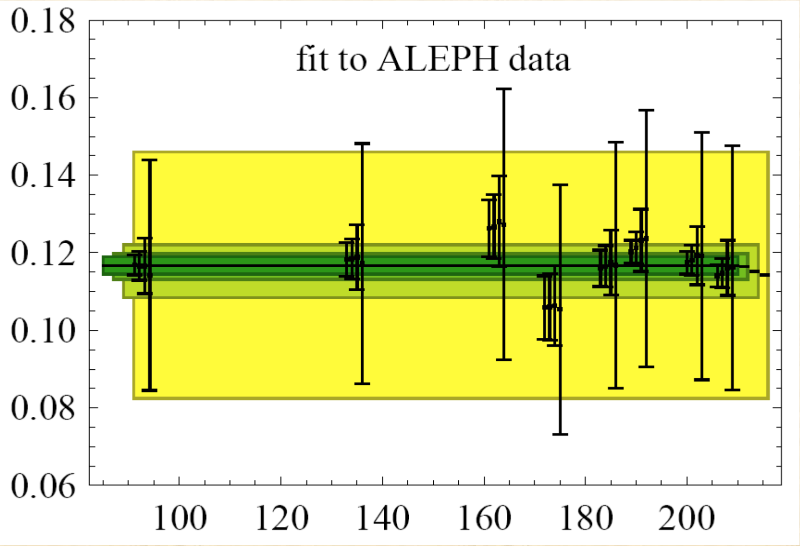


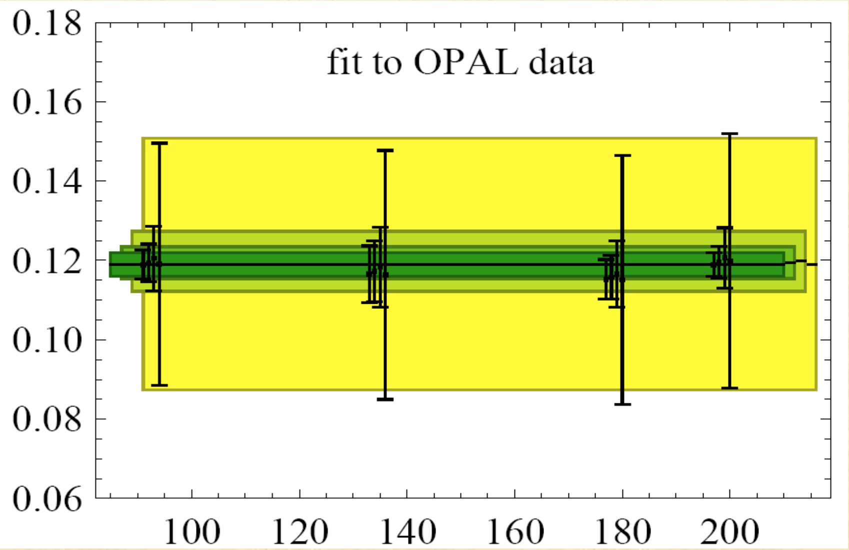


At fixed $\alpha_s(M_Z) = 0.1168$

LEP I AND LEP II

MDS, T. Becher
arXiv:0803.0342





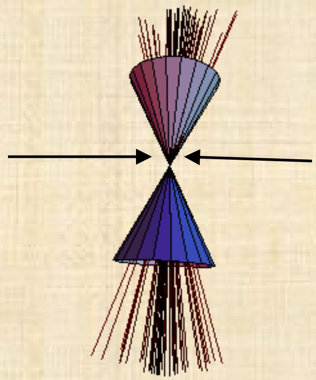
$\alpha_s(M_Z)$ = 0.1172 ±0.002

$\alpha_s(M_Z)$ = 0.1274 ±0.005 (fixed order thrust)

$\alpha_s(M_Z)$ = 0.1176 ±0.002 (World Average)

- Effective field theory
  - is much more convergent than fixed order QCD
  - improves fit to α_s tremendously
  - helps test QCD

JETS AT HADRON COLLIDERS



$e^+e^- \to$ jets

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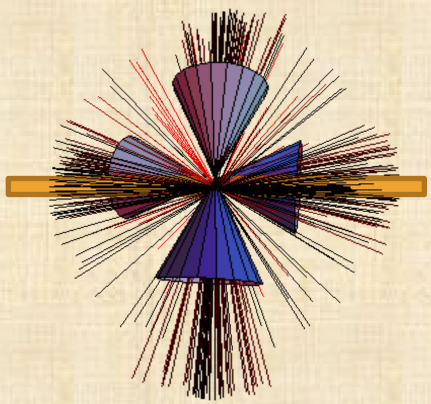
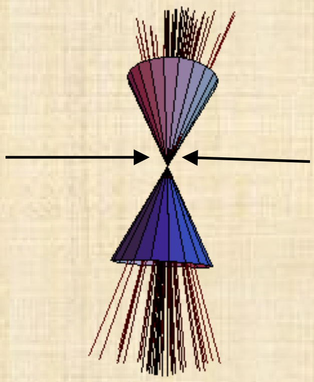


pp → jets

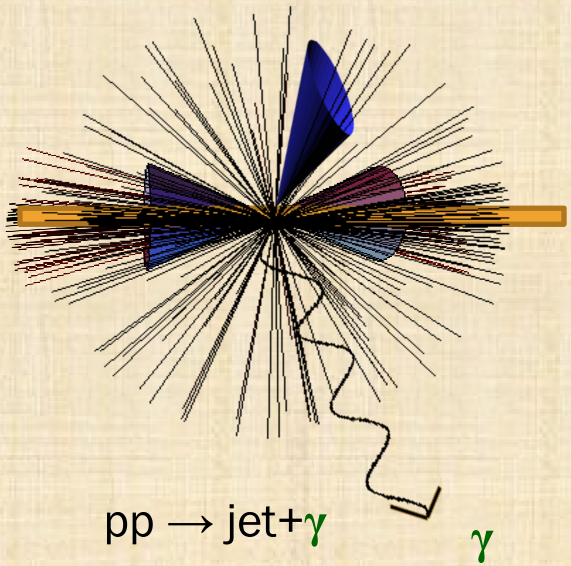
Additional Complications

1. Energy distribution in hadrons is **non-perturbative** ✓
    - Use PDFs
    - Understood in SCET (Drell-Yan, DIS, Higgs production)
2. **Multiple directions** of large energy flow
    - Will angle dependence cancel?
3. **Multiple channels**
    - QQ → QQ, QQ → GG, GG →GG ✓
    - Understood for tt, heavy colored states, ...
4. **Multiple color** configurations
    - Dijets understood in traditional QCD
    - Understood in SCET (B decays, tt, ...)
5. **Observable** must avoid beam
    - Hadronic event shapes? [Salam, Zanderighi...]
    - Energy flow? [Sterman, Kucs, ...]
    - Beam thrust? [Stewart, ...]
    - Dynamical Threshold Enhancement? [Becher, Neubert...]

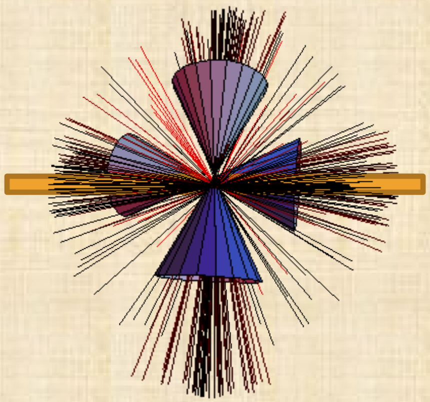
JETS AT HADRON COLLIDERS



$e^+e^- \rightarrow$ jets



pp → jet+γ



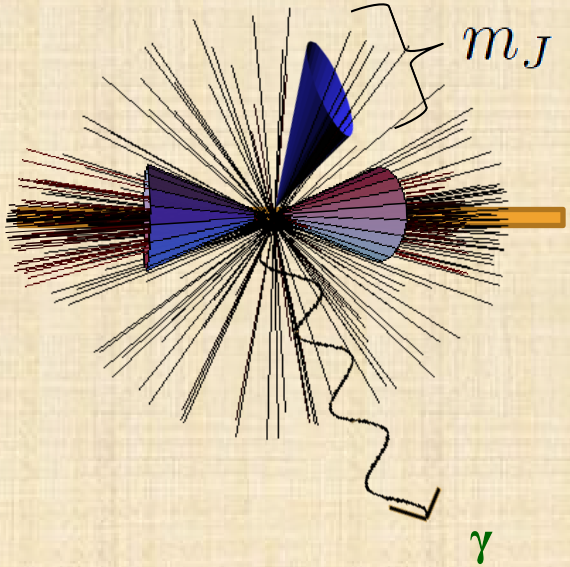
pp → jets

Direct photon production

- Addresses some of the additional complications
  2. Multiple Directions
  3. Multiple Channels (QQ→ G γ and QG→ Qγ)

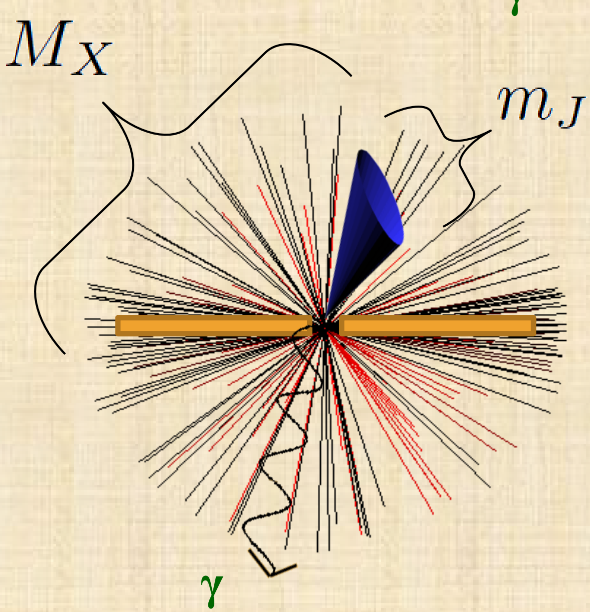
- Important early LHC measurement
  - measure **gluon PDF**
  - calibrate **jet energy scales**

WHAT IS THE OBSERVABLE?



- We want to measure the **jet mass** m_J^2
- We expect **resummation** to be **important** as $m_J^2 \to 0$
- Simplest observables will have few parameters
  - Can we **avoid** dealing with **jet definition**?

  (non-global logs? Start simple!)



Assumption for SCET factorization theorem

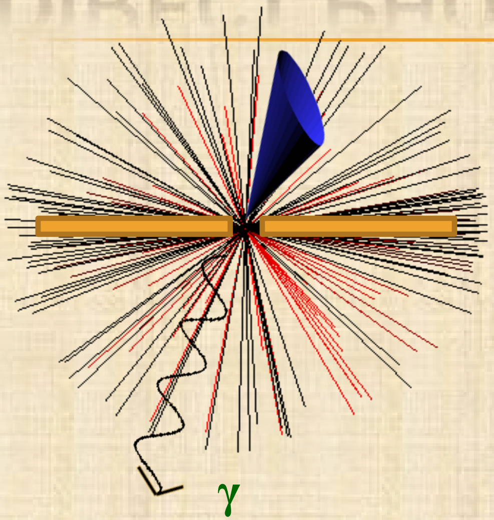
Machine Threshold limit

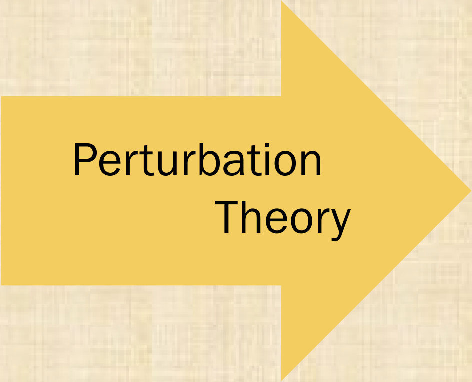
- **Initial state**: 2 protons
- **Final state:** 1 **jet** + 1 photon+ **soft radiation only**

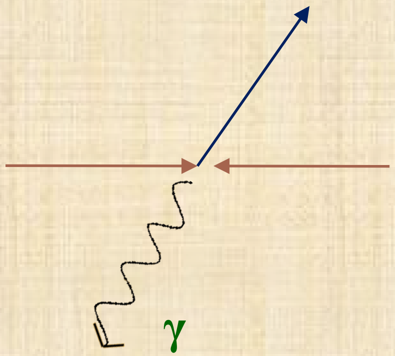
  (no jet-like proton remnants)

- **Observable** is photon p_T and rapidity (y)
- **Inclusive** measurment -- no jet definition necessary

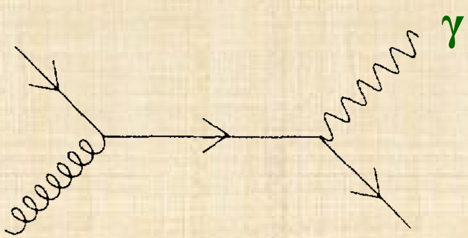
DIRECT PHOTON PRODUCTION

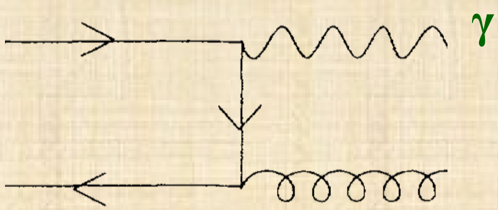






Leading Order



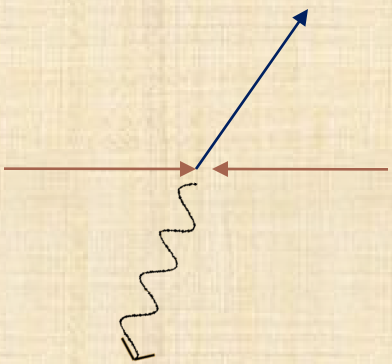


Compton Channel
(important way to measure gluon PDF)

Annihilation Channel

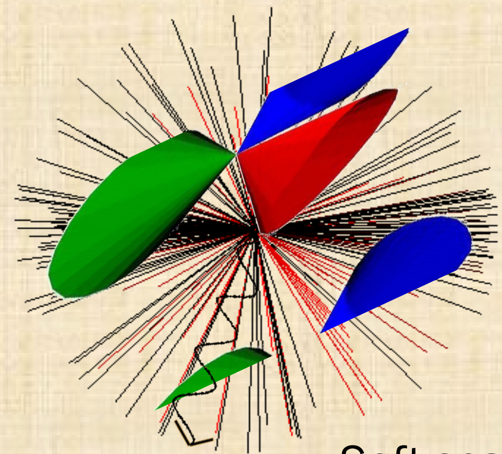
FACTORIZATION IN SCET

$$\mathcal{O}^\nu = \bar{\psi}_{n_1} A^\nu_{n_2} \psi_{n_3} \quad \rightarrow \quad \bar{\chi}_{n_1} \mathcal{A}^\nu_{n_2} \chi_{n_3} \quad \rightarrow \quad \bar{\chi}_1 Y_1^\dagger Y_2 \mathcal{A}_2^{\nu a} \tau^a Y_2^\dagger Y_3 \chi_3$$



Hard scale

Jet scale



Soft scale

$$\langle p_1\, p_2 | \mathcal{O}^\nu(x) \mathcal{O}^\nu(0) | p_1\, p_2 \rangle = \langle p_1 | \bar{\chi}_1 \chi_1 | p_1 \rangle \; \langle 0 | \mathcal{A}_2^\nu \mathcal{A}_2^\nu | 0 \rangle \; \langle p_1 | \bar{\chi}_3 \chi_3 | p_1 \rangle \; \langle 0 | (Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3)(Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3) | 0 \rangle$$

- $\langle p_1 | \bar{\chi}_1 \chi_1 | p_1 \rangle$ → PDF
- $\langle 0 | \mathcal{A}_2^\nu \mathcal{A}_2^\nu | 0 \rangle$ → Jet function
- $\langle p_1 | \bar{\chi}_3 \chi_3 | p_1 \rangle$ → PDF
- $\langle 0 | (Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3)(Y_1^\dagger Y_2 \tau^a Y_2^\dagger Y_3) | 0 \rangle$ → Soft function

FINAL DISTRIBUTION

PDF $\langle p_1|\bar{\chi}_1\chi_1|p_1\rangle$

PDF $\langle p_1|\bar{\chi}_3\chi_3|p_1\rangle$

$$\frac{d^2\sigma_{q\bar{q}}}{dy\,dp_T} = \frac{2}{p_T}\int_{\frac{p_T}{E_{\rm CM}}e^{y}}^{1-\frac{p_T}{E_{\rm CM}}e^{-y}} dv \int_{\frac{p_T}{E_{\rm CM}}\frac{1}{v}e^{y}}^{1} dw \left[(wx_1)f_{q/N_1}(x_1,\mu)\right]\left[x_2 f_{\bar{q}/N_2}(x_2,\mu)\right]$$

$$\times\, \widetilde{\sigma}_{q\bar{q}}(v) H_{q\bar{q}}(p_T,v,\mu)\int dk\, J_g(m_X^2-(2E_J)k,\mu)\, S_{q\bar{q}}(k,\mu)$$

Hard function

- NLO (from QCD)
- SCET: γ_H to 3-loops

Jet function

$\langle 0|\mathcal{A}_2^{\nu}\mathcal{A}_2^{\nu}|0\rangle$

- Quark jet to NNLO
- Gluon jet to NLO
- γ_{Jq} and γ_{Jq} to 3-loops

Soft function

- both channels to NLO
- γ_S to 3-loops (from RG and Casimir scaling)

Direct photon distribution with NNLL resummation + NLO fixed order

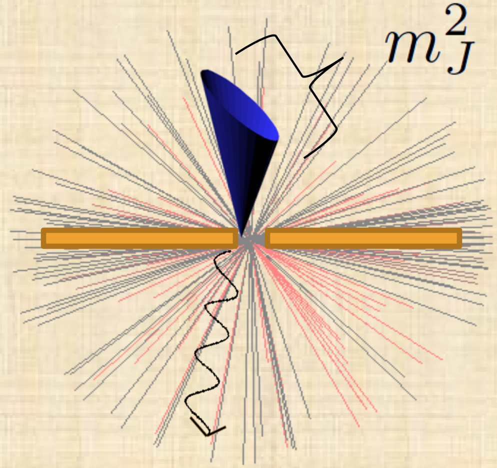
WHAT ARE THE MATCHING SCALES?

Matching scales appear as:

$$\frac{\mu_h^2}{p_T^2}, \quad \frac{\mu_j^2}{m_J^2}, \quad \frac{\mu_s}{\mu_j^2/\mu_h}$$

Hard scale = p_T

Jet scale = m_J?



m_J^2 = mass of **jet**

•**Works** for **thrust**

$$\frac{d\sigma}{dm_J^2} \sim \exp\left[\alpha_s \log\frac{m_J^2}{E_{\rm CM}^2}\right]$$

•**Problematic** for direct photon

•m_J is integrated over, including $m_J = 0$

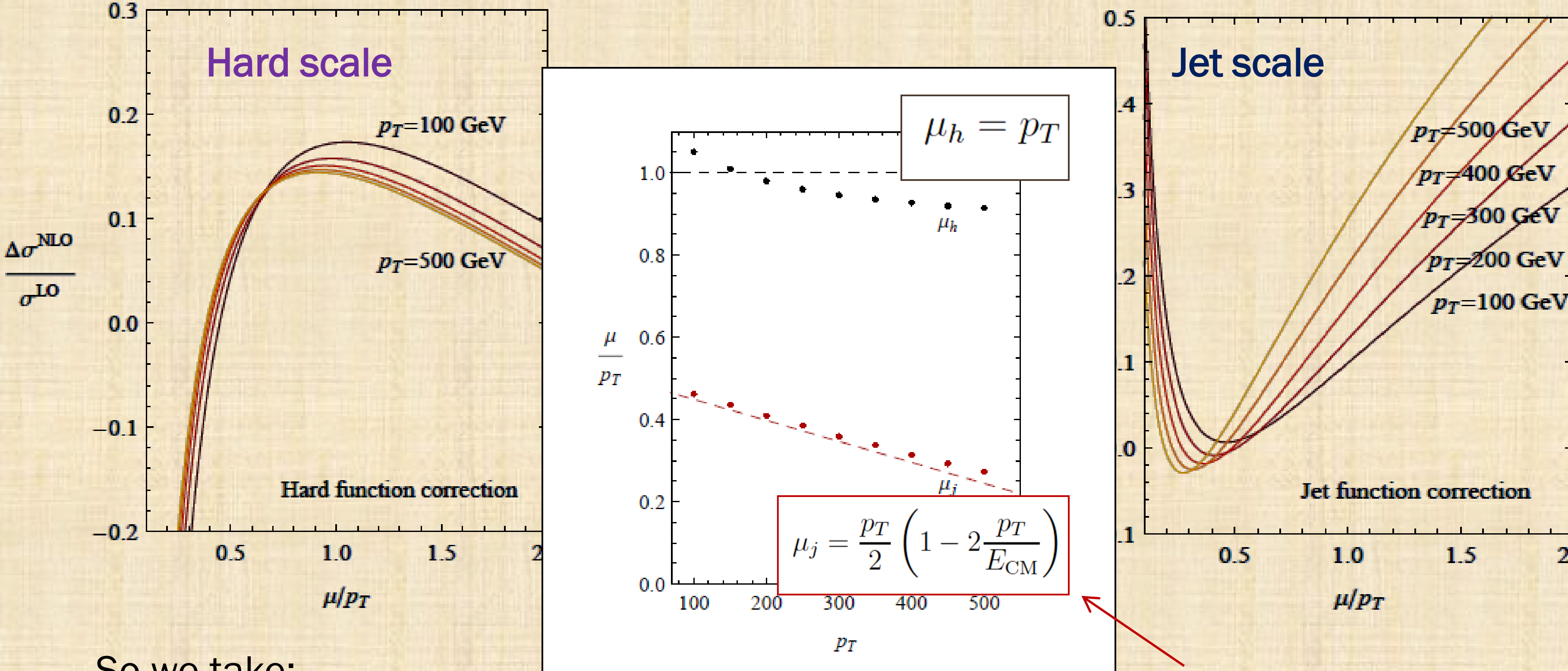
$$\frac{d\sigma}{dM_X^2} = \int dm_J^2 \delta\left(M_X^2 - m_J^2 - (1-x_1)\frac{t}{s} - (1-x_2)\frac{u}{s}\right) f(m_J^2, \cdots)$$

$$f \sim \exp\left[\alpha_s(\mu_J)\log\frac{\mu_J^2}{\mu_h^2}\right] \times \cdots \rightarrow \exp\left[\alpha_s(m_J)\log\frac{m_J^2}{p_T^2}\right] \times \cdots$$

• probes Landau pole of QCD → unphysical power corerctions

All matching scales should depend only **physical**, **observable scales** –*i.e.* p_T

NATURAL SCALES



note that

$$\mu_J = \langle m_J \rangle \lesssim p_T^\gamma$$

So we take:

$$\mu_h = p_T$$

$$\mu_j = \frac{p_T}{2}\left(1 - 2\frac{p_T}{E_{CM}}\right)$$

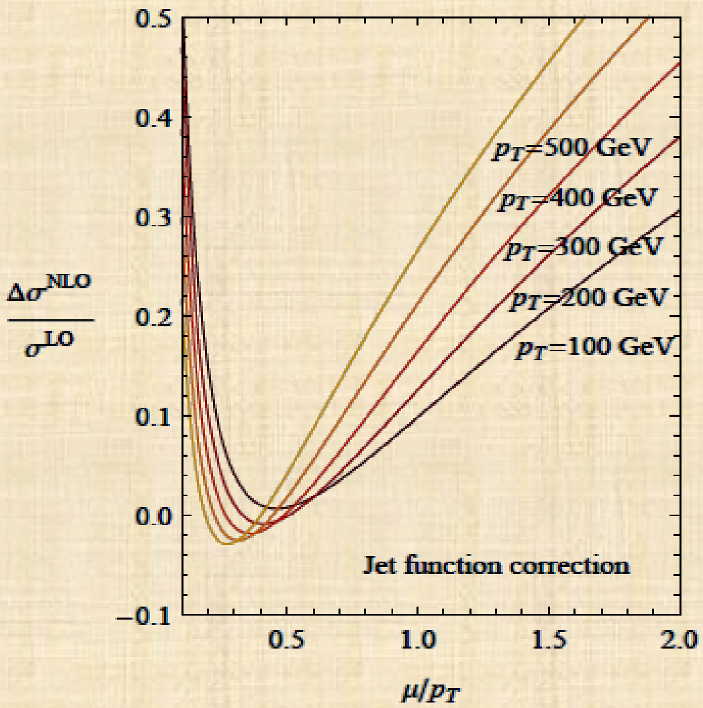
$$\mu_s = \mu_j^2/\mu_h$$

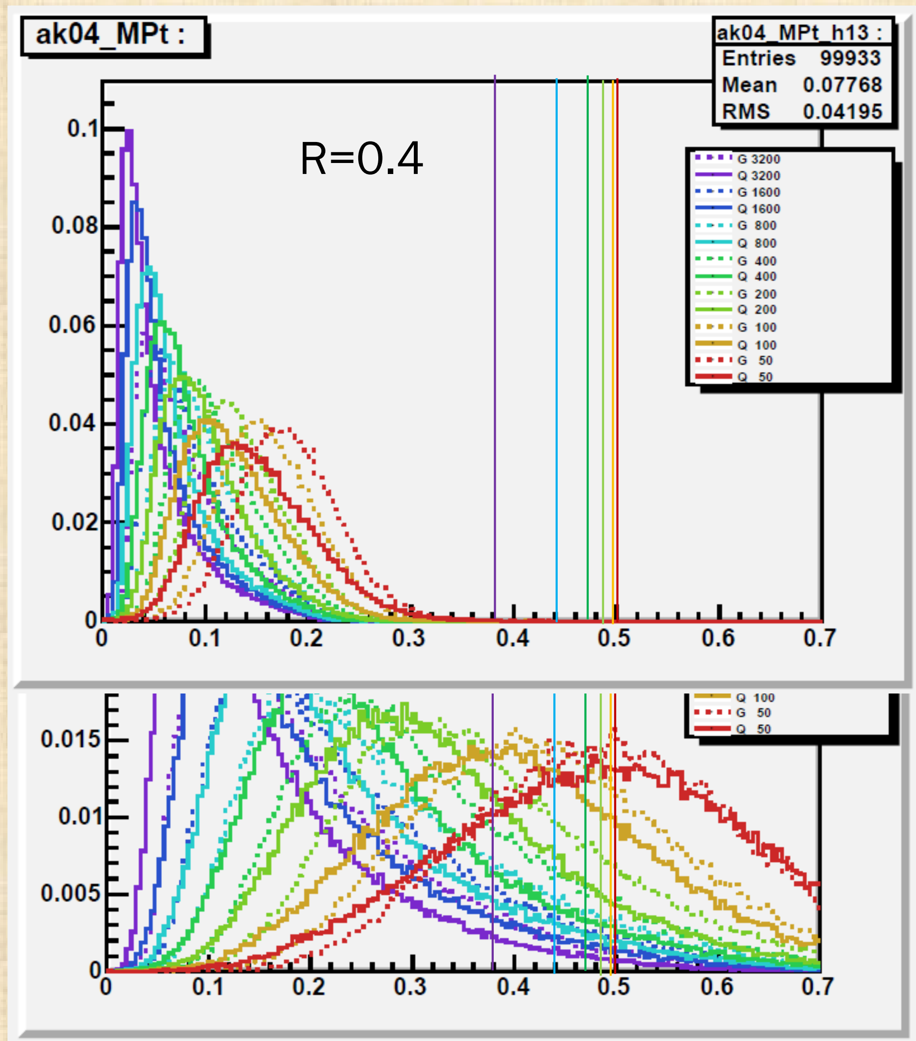
Always well above Λ_{QCD}

- avoids unphysical region

JET MASSES

Rule of thumb "m = 0.2 pt"





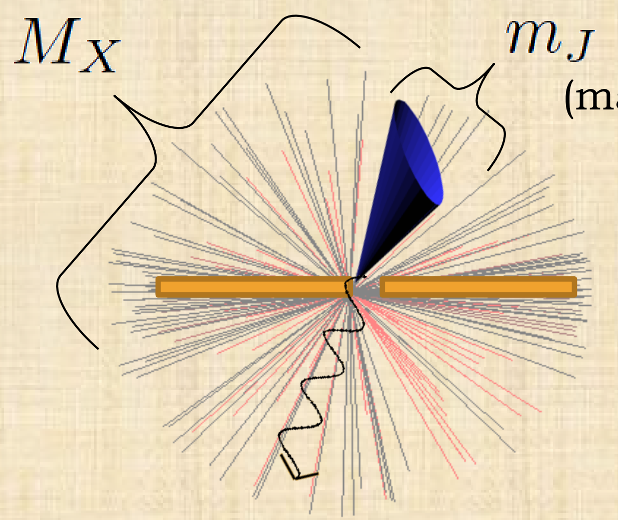
μ_J is the ***average*** jet mass

DYNAMICAL THRESHOLD ENHANCEMENT

(mass of everything but the photon)

We have found

$$\mu_J = \langle m_J \rangle \lesssim p_T^\gamma \lll M_X \sim E_{\mathrm{CM}}$$



large

$$M_X^2 = m_J^2 + (1-x_1)\frac{t}{s} + (1-x_2)\frac{u}{s}$$

small

Dynamical Threshold Enhancement

Resummation unexpectedly important at hadron collliders!

- What about x not being close to 1?

MATCHING

- PDFs evolve with DGLAP equations

$$\frac{d\, f_i(x,\mu)}{d\log\mu} \sim \int dz \left\{ \alpha_s \left[\frac{1+z^2}{1-z}\right]_+ + \cdots \right\} f_i(\frac{x}{z},\mu)$$

  - μ_f dependence in exact NLO distribution cancels
    μ_f dependence of PDFs -- to order α_s^2

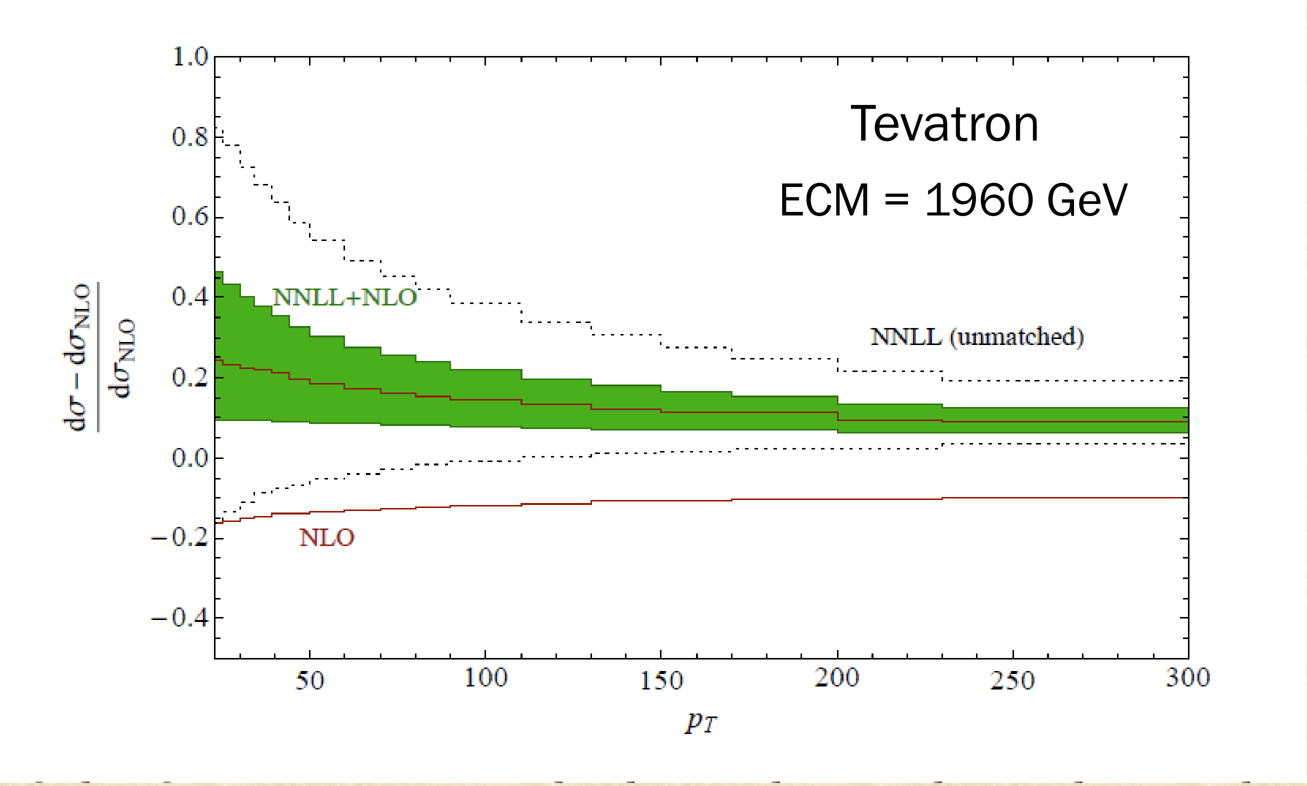
- SCET valid near threshold ($x_1 \sim 1$ and $x_2 \sim 1$)
  - μ_f would cancel if

$$\frac{d\, f_i(x,\mu)}{d\log\mu} \sim \int dz \left\{ \alpha_s \left[\frac{2}{1-z}\right]_+ + \cdots \right\} f_i(\frac{x}{z},\mu)$$

- By matching NNLL resummation to NLO fixed order
  - μ_f dependence cancels exactly to order α_s^2
  - μ_f dependence cancels partially to order α_s^4

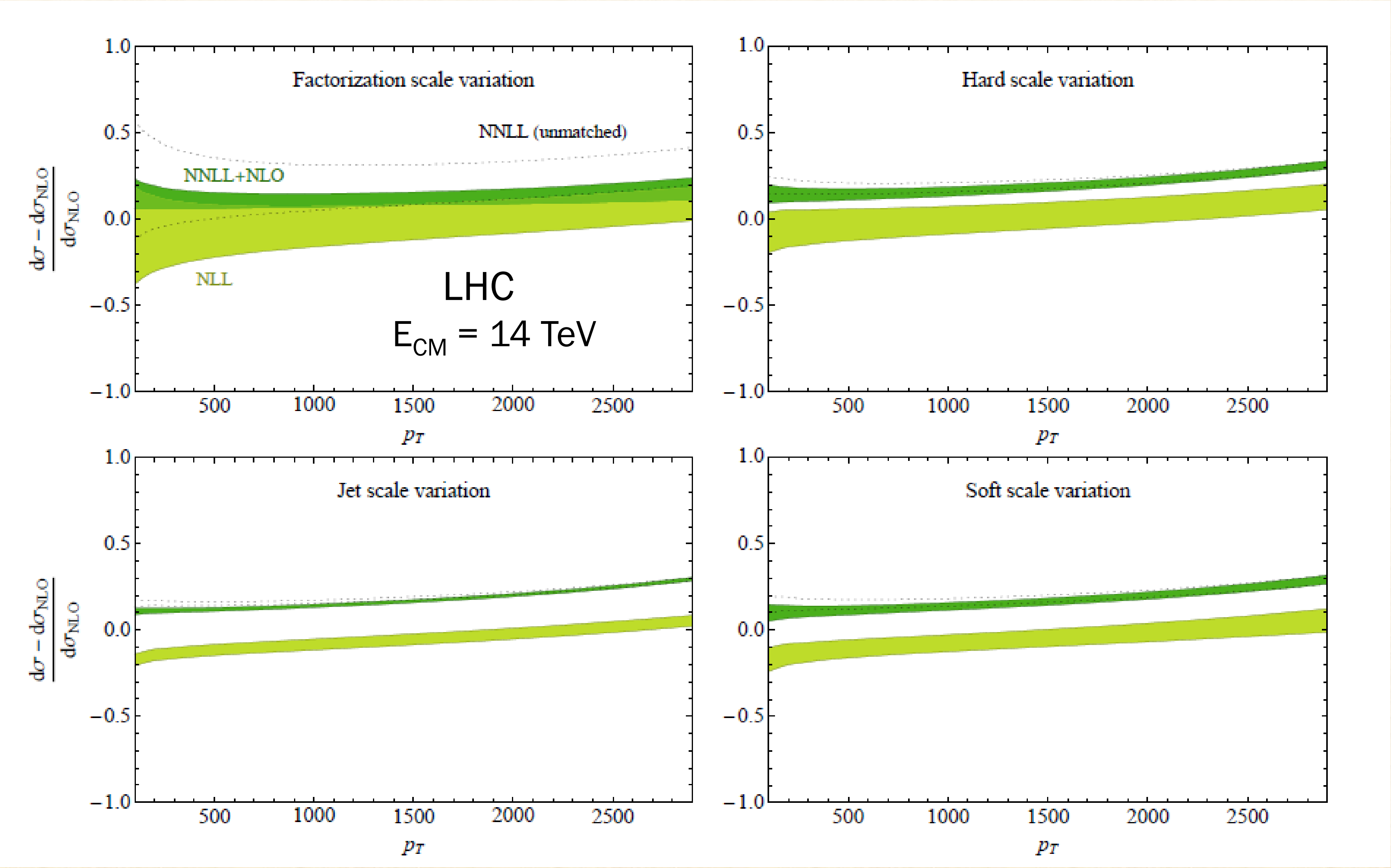
MATCHING

$$\left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{matched}} = \left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{NNLL}} - \left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{NNLL}}_{\mu_h=\mu_j=\mu_s=\mu_f} + \left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{NLO}}_{\mu_f}$$



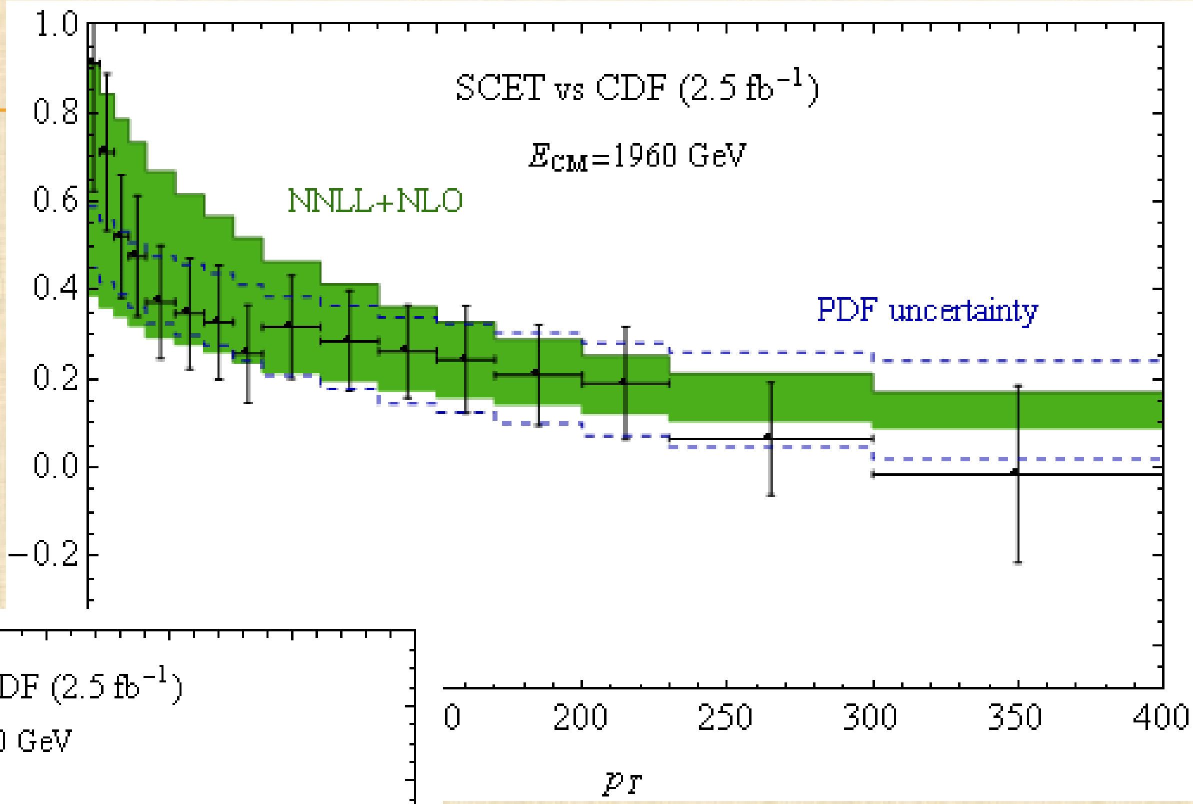
Matching to exact NLO distribution reduces μ_f dependence

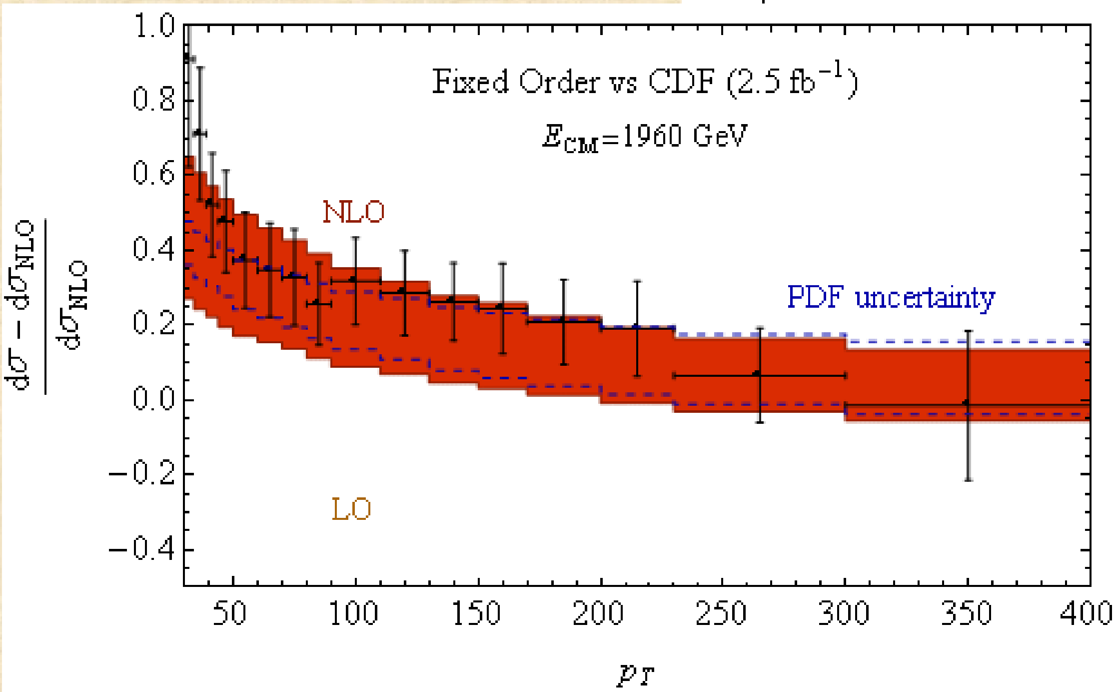
SCALE UNCERTAINTIES



RESULTS

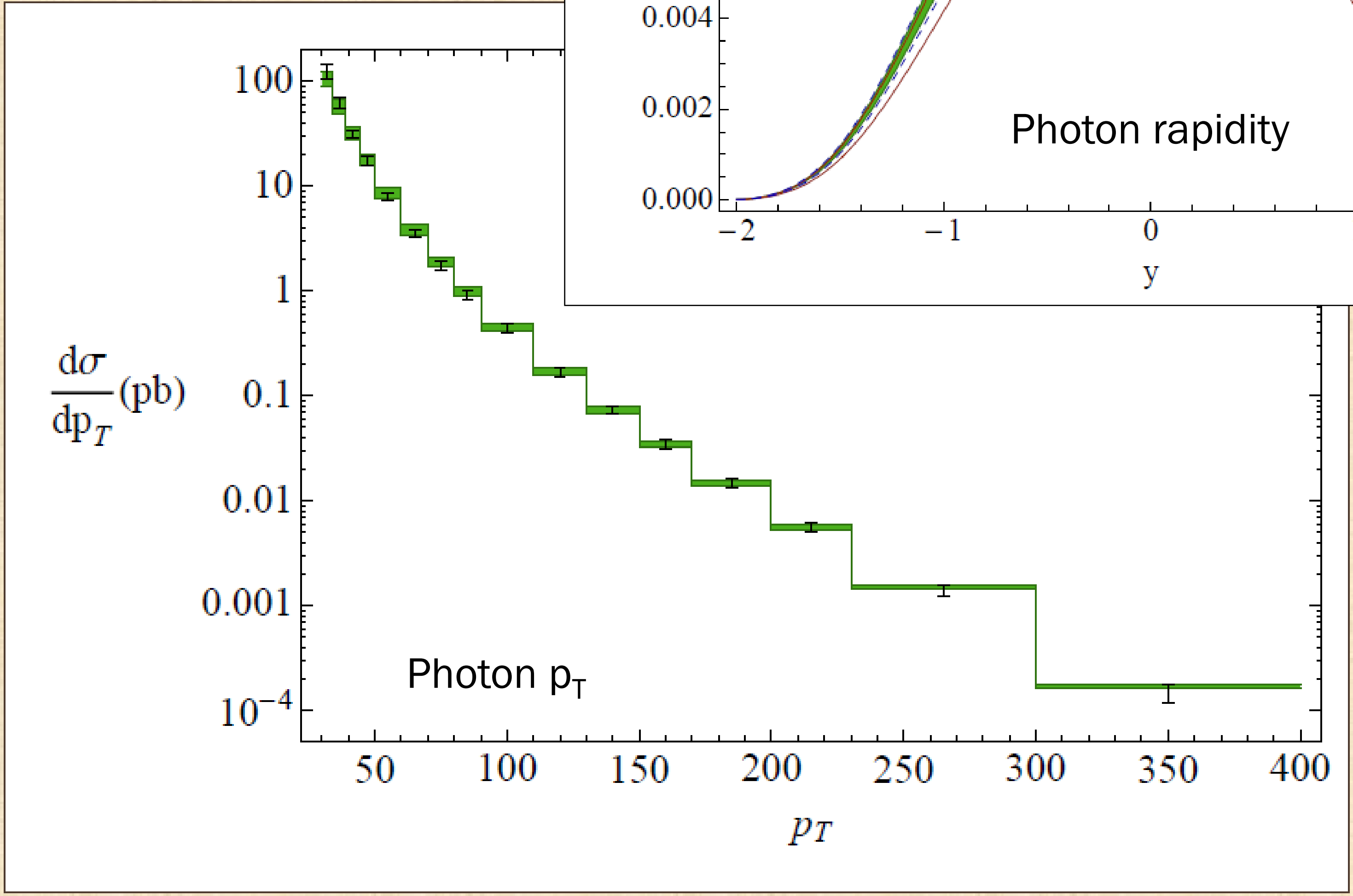
- Corrected for hadronization with PYTHIA
- Corrected for photon isolation with JETPHOX

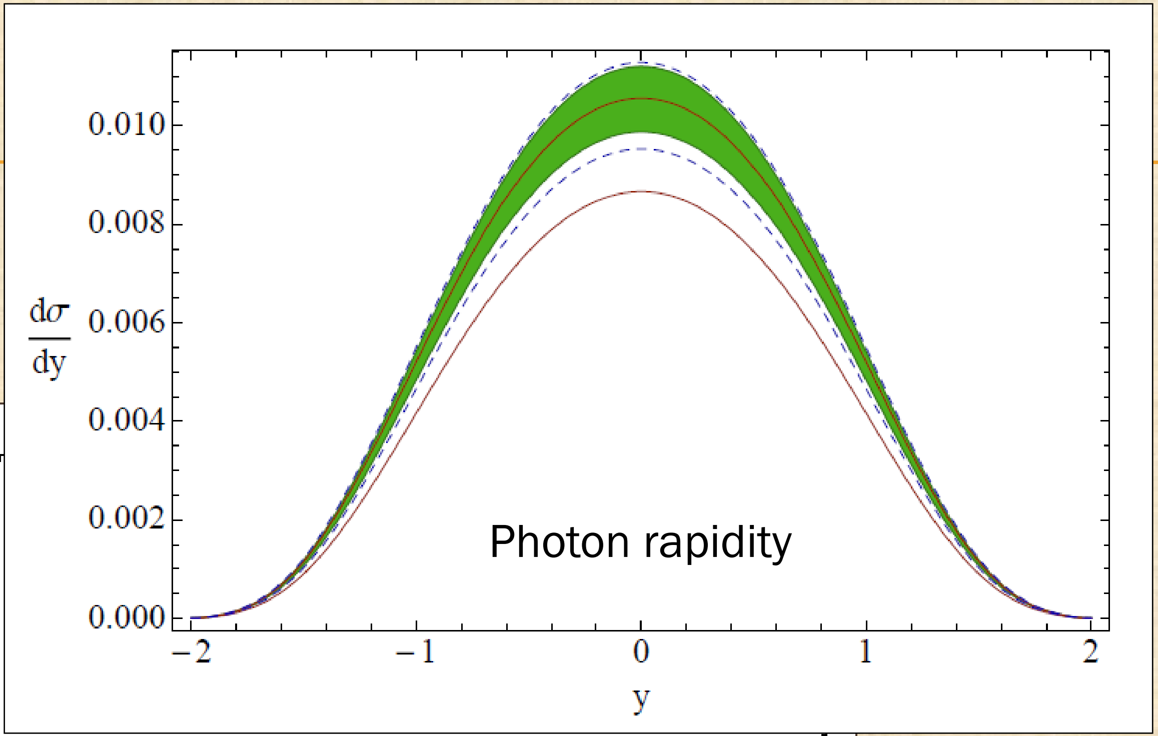




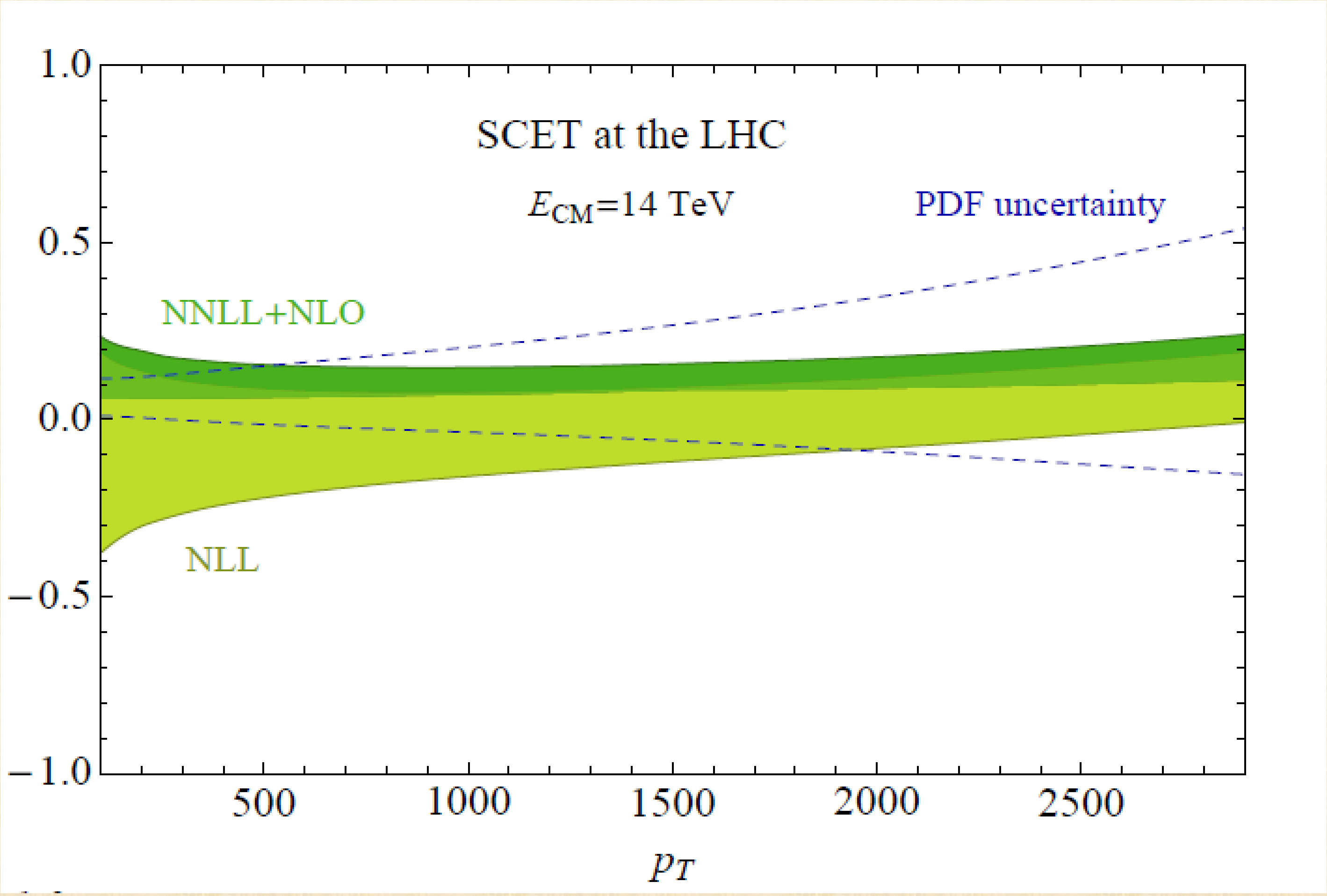
RESULTS

SCET vs CDF data

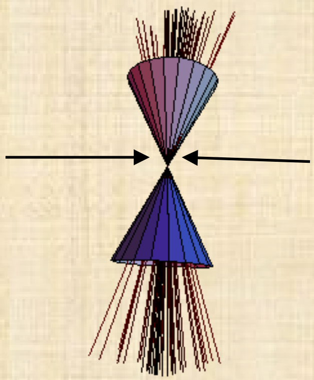




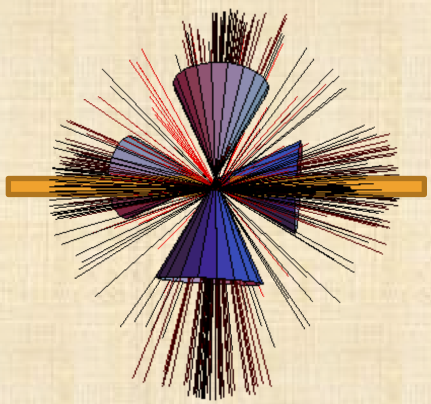
PREDICTIONS FOR LHC



CLOSE TO JETS SHAPES



$e^+e^- \rightarrow$ jets



$pp \rightarrow$ jets

Additional Complications

1. Energy distribution in hadrons is non-perturbative ✓
   - Use PDFs
   - Understood in SCET (Drell-Yan, DIS, Higgs production)

2. Multiple directions of large energy flow ✓
   - Will angle dependence cancel? Yes.

3. Multiple channels ✓
   - $QQ \rightarrow QQ$, $QQ \rightarrow GG$, $GG \rightarrow GG$

4. Multiple color configurations ✓
   - Work in progress with R. Kelley

5. Observable must avoid beam
   - Beam functions?
   - Exclusive jets
   - Threshold Thrust -> jet pT?
   - Dynamical threshold enhancement?

CONCLUSIONS

- Understanding jets is critical for the LHC
- Resummation can be done with SCET
  - Great improvements for LEP event shapes
  - Great improvements for direct photon spectrum
  - Resummation important even at moderate $x<1$
- Next steps
  - W/Z + jets (work in progress with T. Becher)
  - Dijets (work in progress with R. Kelley)
  - Exclusive Monte Carlo event generation (long term)