Jet Pull

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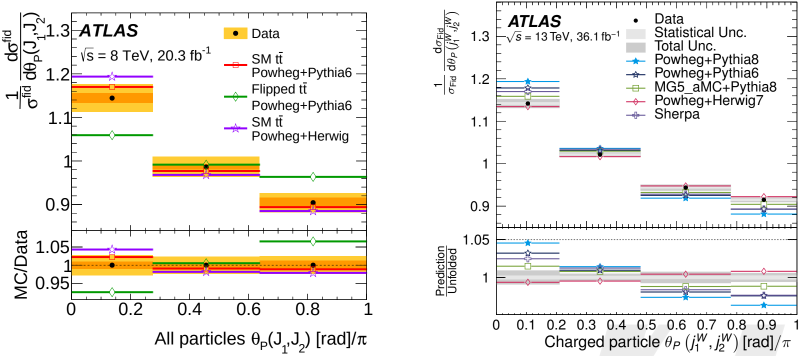
Workshop on Parton Showers and Resummation
Vienna, 11-14 Jun, 2019

With: Simone Marzani
Andrew Larkoski

Based on:
arXiv:1903.02275 + ongoing work

Motivation

- Experimental motivation



difference between state-of-the-art simulations and data[ATLAS, 1506.05629,1805.02935]

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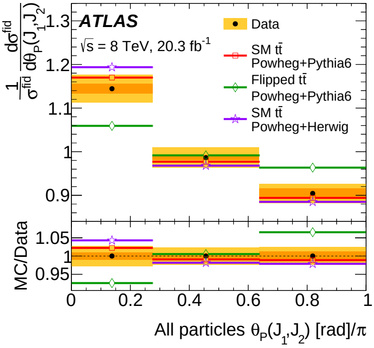

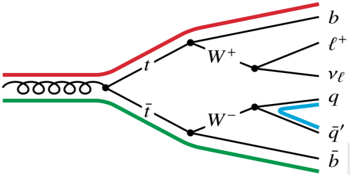

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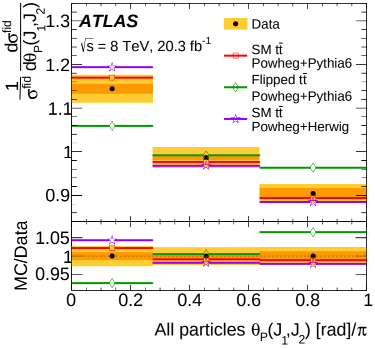
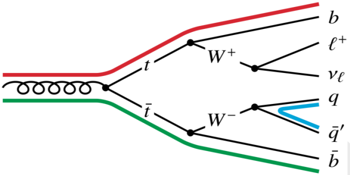




difference between state-of-the-art simulations and data[ATLAS, 1506.05629,1805.02935]

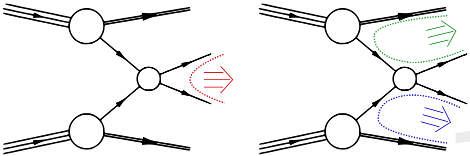
- Theoretical motivation: challenge of IRC unsafe observable

Outline

1. *Introduction*
   - definition of pull
   - Sudakov safe techniques
2. *Theoretical predictions at small q_T*
   - standard q_T resummation formalism
   - pull angle: comparison with MC and data
3. *IRC safe observable*
   - analog from a_T distribution
   - resummed result
4. *Summary and Outlook*

Colour Flow

- difference between colour singlet (signal) and colour octet (background)



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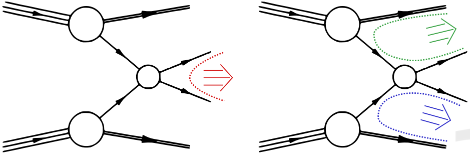

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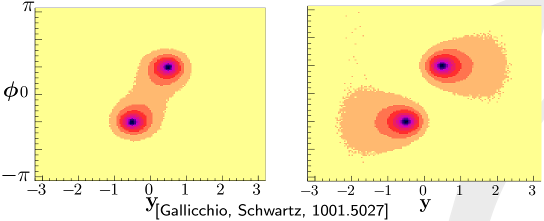
- MC shower picture:



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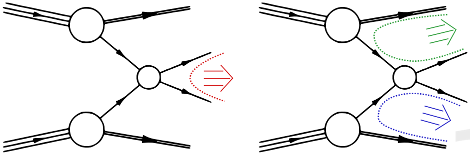

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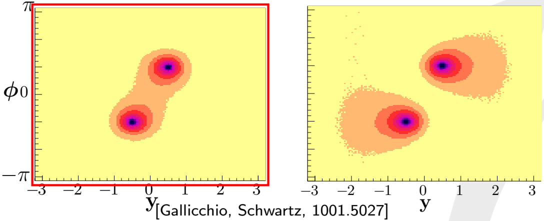

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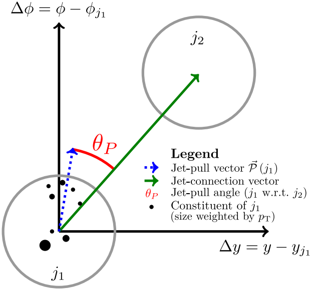
Definition of Pull

- Construction of the jet pull



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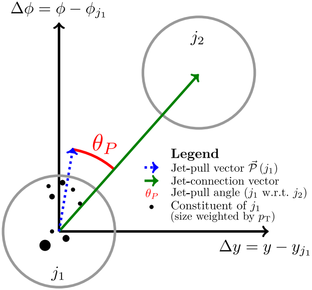

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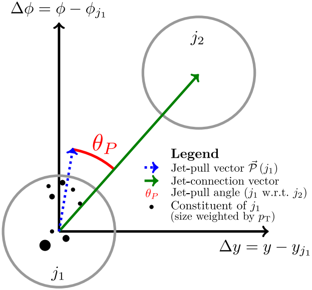

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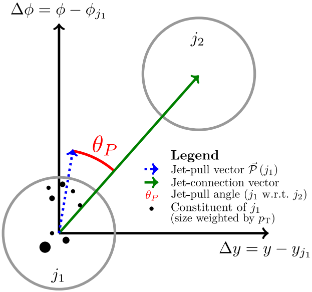

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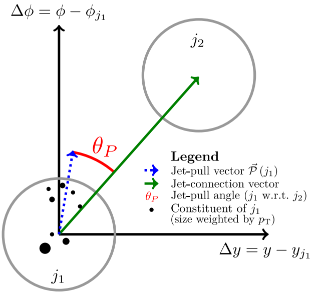

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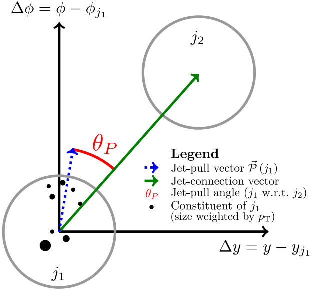

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IRC safety vs Sudakov safety

IRC safety

The complete cancellation of infrared and collinear singularity require the IRC safe observable as

$$O_n(p_1...p_i...p_n) \to O_{n-1}(p_1...p_{i-1}, p_{i+1}...p_n), \;\; if \; p_i \to 0$$
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- Sudakov safety: with the help of all-order resummation, the Sudakov factor will act as the regulator for the double differential cross section

Sudakov safe techniques

Formalisms for the calculation:

- Approach 1: Double differential NLL resummation

$$\frac{1}{\sigma}\frac{d\sigma^{res}}{d\vec{t}} = \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{b}\cdot\vec{t}} e^{-R(b)}$$

- Approach 2: Joint probability

$$p(\phi_p) \approx \int dt\, p_{res}(t)\, p_{fo}(\phi_p|t)$$

$$= \int dt\, e^{-R(t)} \frac{d^2\sigma^{fo}}{dt d\phi_p}$$

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We can avoid the puzzle from the double differential resummation, by just resum the pull magnitude

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Review: q_T Resummation formalism

For the general q_T like observable $V\left(\vec{k}\right)$, $\vec{k} = \sum_i \vec{k}_{\perp i}$, the all-order differential cross section is

$$\frac{d^2\sigma}{dV} = \mathcal{V} \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} d\left[k_i\right] \left|M\left(p_1, p_2, k_1 \cdots k_n\right)\right|^2 \delta(V - \tilde{V}\left(k_1 \cdots k_n\right))$$

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n-particle final state real emissions can be factorized as

$$\left|M\left(p_1, p_2, k_1 \cdots k_n\right)\right|^2 = \left|M_0\left(p_1, p_2\right)\right|^2 \frac{1}{n!} \left|M\left(k_i\right)\right|^2 \cdots \left|M\left(k_n\right)\right|^2$$

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Simplify the QCD amplitude with single gluon emission:

soft part:

$$\left|M\left(k_1\right)\right|^2 = C_F\frac{2p_1p_2}{(k_1p_1)(k_1p_2)}$$

collinear part:

$$\left|M\left(z\right)\right|^2 = P(z) = C_F\frac{1+(1-z)^2}{z}$$

Review: q_T Resummation formalism

- Collinear n gluon emissions, with $R = 0.4$:

$$\vec{t} = \sum_{i=1}^{n} \vec{t}_i \left(k_i\right)$$

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$$\frac{d^2\sigma}{d\vec{t}} = \mathcal{V} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} d\left[k_i\right] P\left(z_i\right) \delta^{(2)} \left(\vec{t} - \sum_{n=0}^{\infty} \vec{t}_i \left(k_i\right)\right)$$

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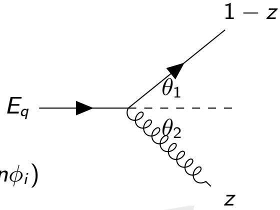
- Sum over all emissions can be done as

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\vec{t}} = \frac{1}{4\pi^2}\int d^2\vec{b}e^{i\vec{b}\cdot\vec{t}}exp\left[-\int d[k]P\left(z\right)\left(1 - e^{-i\vec{b}\cdot\vec{t}_1}\right)\right]$$

$$\equiv \frac{1}{4\pi^2}\int d^2\vec{b}e^{i\vec{b}\cdot\vec{t}}e^{-R(b)}$$



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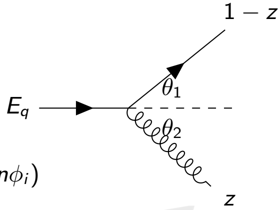
Resummed results (pull magnitude)



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$$\vec{t_1} = z\left(1 - z\right)\left|1 - 2z\right|\theta^2 \left(cos\phi, sin\phi\right)$$

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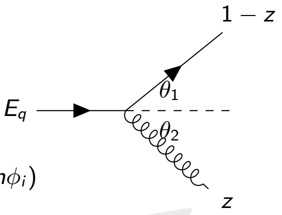

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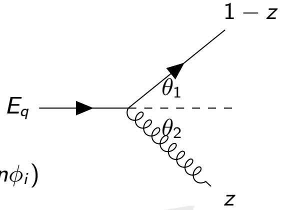

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- For the pull magnitude, simply integrate over the b-space azimuthal angle and the pull angle ϕ_p

$$\frac{1}{\sigma}\frac{d\sigma}{dt} = t\int_0^{\infty} bdbJ_0\left(bt\right)e^{-R(b)}$$

Fixed-order result

- Double differential distribution

$$\frac{d^2\sigma}{dt\,d\phi_p} = \frac{\alpha_s}{\pi^2}\frac{C_F}{t}\Big[\log\frac{4\tan^2\frac{R}{2}}{t} - \frac{3}{4}$$

$$+ 2\cot\phi_p\ \tan^{-1}\frac{\frac{\tan\frac{R}{2}}{\tan\frac{\theta_{12}}{2}}\sin\phi_p}{1-\frac{\tan\frac{R}{2}}{\tan\frac{\theta_{12}}{2}}\cos\phi_p} - \log\Big(1+\frac{\tan^2\frac{R}{2}}{\tan^2\frac{\theta_{12}}{2}} - 2\frac{\tan\frac{R}{2}}{\tan\frac{\theta_{12}}{2}}\cos\phi_p\Big)\Big]$$

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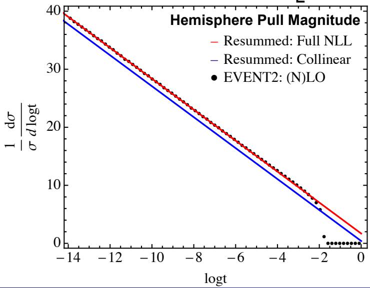

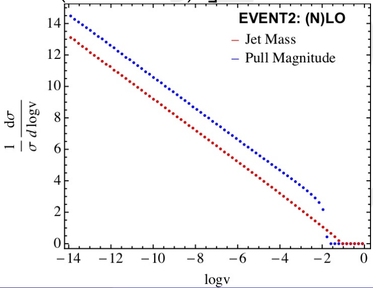

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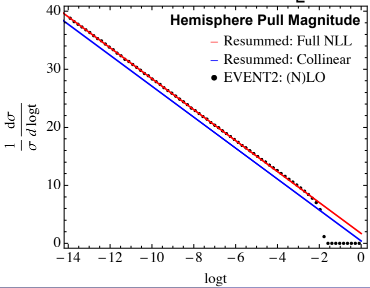
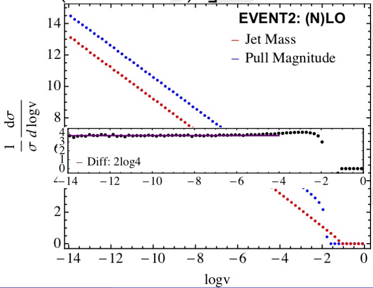
$$\frac{d^2\sigma}{dt\,d\phi_p} = \frac{\alpha_s}{\pi^2}\frac{C_F}{t}[\log\frac{4\tan^2\frac{R}{2}}{t} - \frac{3}{4}$$

$$+ 2\cot\phi_p \ \tan^{-1}\frac{\frac{\tan\frac{R}{2}}{\tan\frac{\theta_{12}}{2}}\sin\phi_p}{1-\frac{\tan\frac{R}{2}}{\tan\frac{\theta_{12}}{2}}\cos\phi_p} - \log(1+\frac{\tan^2\frac{R}{2}}{\tan^2\frac{\theta_{12}}{2}} - 2\frac{\tan\frac{R}{2}}{\tan\frac{\theta_{12}}{2}}\cos\phi_p)]$$

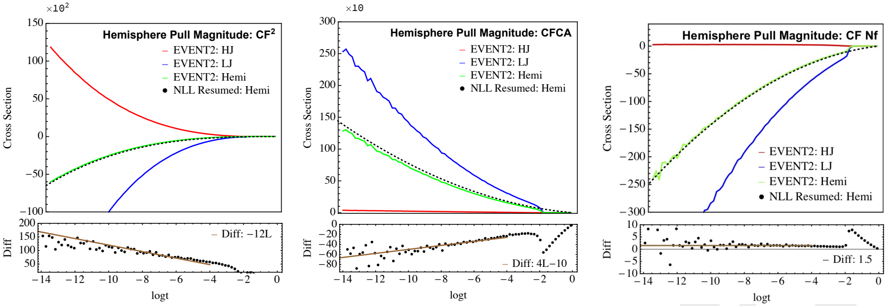
- Magnitude of pull

$$\frac{d\sigma}{dt} = \frac{\alpha_s}{\pi}\frac{C_F}{t}\left[\log\frac{1}{t} - \frac{3}{4} - \log\left(\frac{1-\frac{\tan^2\frac{R}{2}}{\tan^2\frac{\theta_{12}}{2}}}{4\tan^2\frac{R}{2}}\right)\right].$$





For the higher order(NNLO) comparison with EVENT2:



Structure of NLL resummation:[M. Dasgupta G.P. Salam, hep-ph/0104277]

$$\Sigma(t) = (1 + \alpha_s C_1^{(q)})S(\alpha_s L)e^{-R_q(\alpha_s C_F, L)} + \alpha_s C_1^{(g)} e^{-R_g(\alpha_s C_A, L)}$$

Perturbative joint distribution

- Relation between subjet angle and boost angle:

$$m^2 = 2E_1E_2\,(1 - cos\theta_{12}) \Rightarrow cos\theta_{12} = 1 - \frac{2m^2}{E^2}\frac{1}{1-\beta^2 cos\theta}$$

$$\Rightarrow \theta_{12min} \approx \frac{2}{\gamma}$$

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- The subjet angle distribution is

$$p(cos\theta_{12}) = \frac{1}{\gamma^2}\frac{\Theta\left(1 - \frac{2}{\gamma^2} - cos\theta_{12}\right)}{\left(1 - cos\theta_{12}\right)^{3/2}\sqrt{1-\frac{1}{\gamma^2}}\sqrt{1-\frac{2}{\gamma^2} - cos\theta_{12}}}$$

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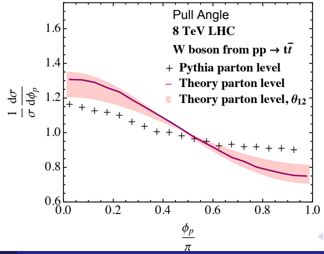
- By convolve with the result of Sudakov safe calculation, the full perturbative joint distribution is

$$p_{perp}\left(t, \phi\right) = \int_{-0.62}^{-0.18} dcos\theta_{12}\, p_{res}\left(t\right) p_{fo}\left(t|\phi_p\right) p\left(cos\theta_{12}\right)$$



Non-perturbative correction

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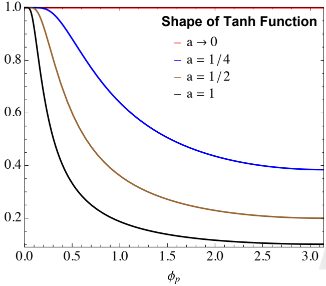
- The angle dependent part:



Compare with MC and data

Finally the pull angle distribution can be obtained by

$$p(\phi_p) = \int_0^\infty dt \int_0^\infty dt' \int_0^{2\pi} d\phi' \int_0^\infty dt'' \int_0^{2\pi} \frac{d\phi''}{2\pi} p_{perp}(t', \phi') \, p_{np}(t'', \phi'') \times \delta\left(\phi_p - cos^{-1}\frac{t' cos\phi' + t'' cos\phi''}{t}\right) \delta\left(t - \sqrt{t'^2 + t''^2 + 2t' t'' cos(\phi' - \phi'')}\right)$$

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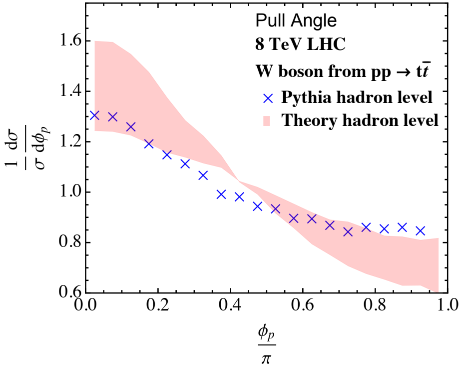

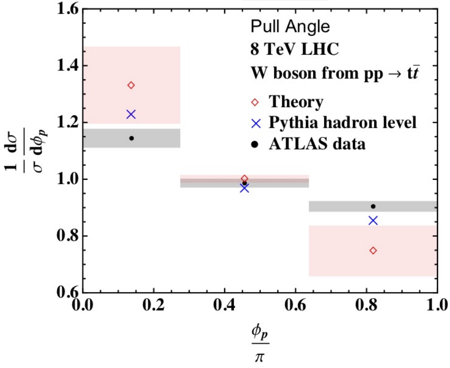

Outline

Compare a_T with q_T distribution

- Definition of t_x and a_T distribution [A. Banfi, M. Dasgupta and R. M. Duran Delgado, 0909.5327]

$$a_T = |\sum_i k_{ti} sin\phi_i|$$

$$t_x = |\sum_i t_i cos\phi_i|$$

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$$= \alpha_S C_F \left(log^2 \frac{M}{2a_T} - \frac{3}{2} log \frac{M}{2a_T} + \frac{\pi^2}{12} \right)$$

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Resummed result for t_x

- Resummation formalism for t_x

$$\frac{d\sigma}{dt_x} = \frac{1}{\pi}\int_0^{+\infty} dbcos\left(bt_x\right) e^{-R(|b|)}$$

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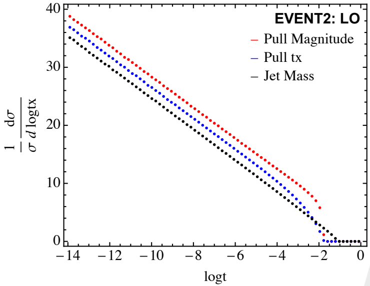

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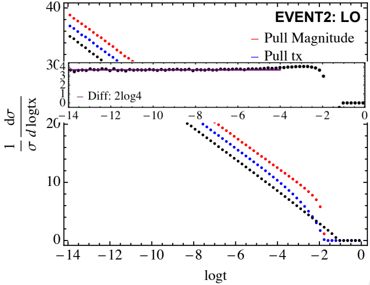

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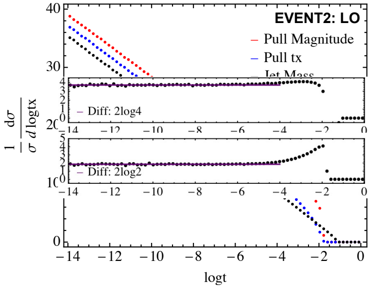

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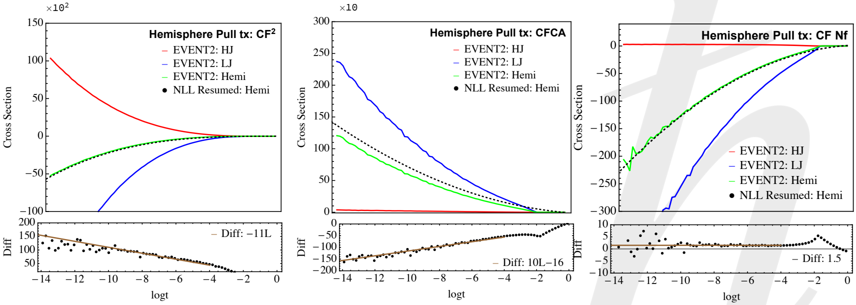

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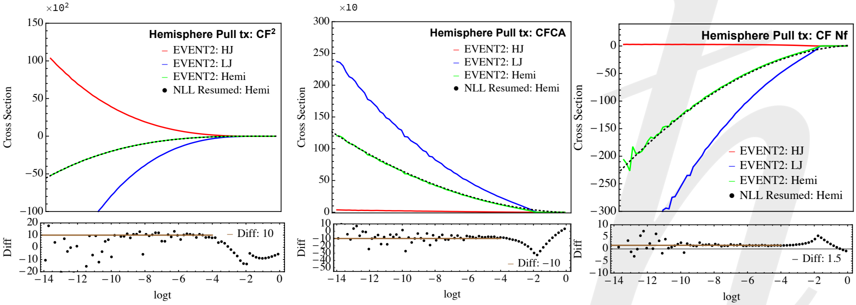
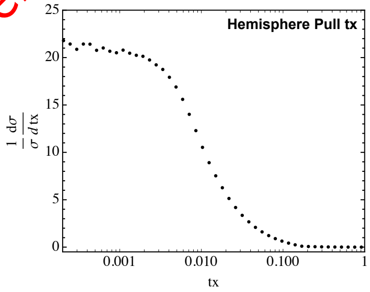
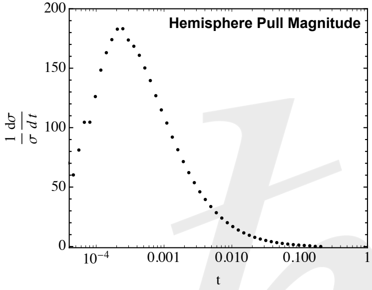


All order results

Preliminary

- (N)LO+NLL matching with EVENT2





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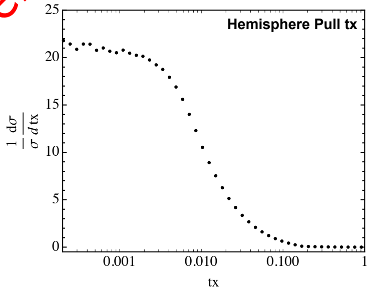

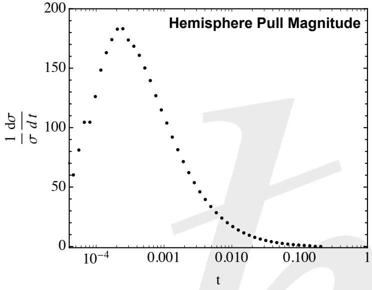

- Non Sudakov suppression for t_x:

$$\frac{d\sigma}{dt_x} = \frac{1}{\pi}\int_0^\infty db\cos(bt_x)\, e^{-\frac{\alpha_s C_F}{2\pi}\log^2 b} = \frac{1}{\pi}\int_0^\infty db e^{-\frac{\alpha_s C_F}{2\pi}\log^2 b}\left[1 + O\left(t_x^2\right)\right]$$

$$= \sqrt{\frac{2}{\alpha_s C_F}}\, e^{\frac{\pi}{2\alpha_s C_F}} + O\left(t_x^2\right)$$

Outline

1. *Introduction*
   - definition of pull
   - Sudakov safe techniques
2. *Theoretical predictions at small q_T*
   - standard q_T resummation formalism
   - pull angle: comparison with MC and data
3. *IRC safe observable*
   - analog from a_T distribution
   - resummed result
4. *Summary and Outlook*

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- With the help of Sudakov safe techniques, we present the first theoretical prediction for the pull angle.
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Thank you for your attention

Extra slides

Backup: Double differential NLL formalism

For $\vec{t} = (t, \phi_p)$

- Missing NLL term for pull angle

$$\frac{d\sigma^{NLO}}{tdtd\phi_p} = \frac{\alpha_s}{2\pi^2}\frac{C_F}{t^2}\left[log\frac{4tan^2\frac{R}{2}}{t} - \frac{3}{4} + f\left(\phi_p, R, \theta_{12}\right)\right]$$

$$\frac{d\sigma^{res\cdot exp}}{tdtd\phi_p} = \frac{\alpha_s}{2\pi^2}\frac{C_F}{t^2}\left[log\frac{4tan^2\frac{R}{2}}{t} - \frac{3}{4} - log\left(1 - a\left(R, \theta_{12}\right)\right)\right]$$

- Check pull magnitude

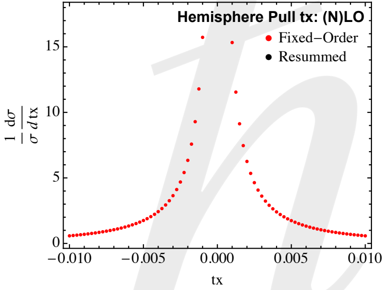
$$\int_0^{2\pi}\frac{d\phi_p}{2\pi}\frac{f\left(\phi_p\right) + log\left(1 - a^2\right)}{t^2} \equiv \int_0^{2\pi}\frac{d\phi_p}{2\pi}\frac{g\left(\alpha_s, \phi_p\right)}{t^2} = 0$$

For $\vec{t} = (t_x, t_y)$

- t_x from the joint distribution

$$\frac{d\sigma}{dt_x} = \int d^2t\frac{d^2\sigma}{tdtd\phi}\delta\left(t_x - tcos\phi\right)$$

- Compare with resummed result



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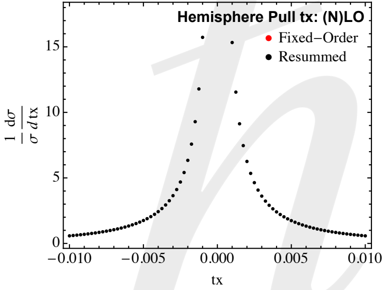


Backup: (N)LO+NLL

Improvement for the fixed-order results:

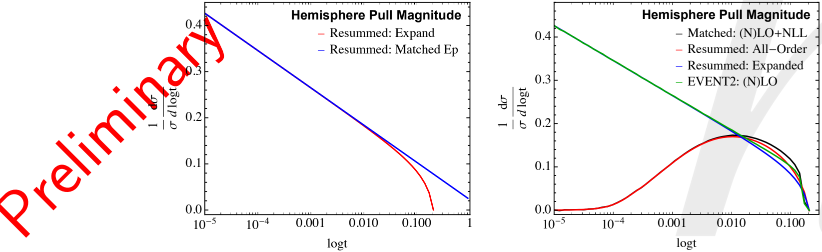
$$\frac{1}{\sigma}\frac{d\sigma_{(N)LO+NLL}}{dlogt} = \frac{1}{\sigma}\left[\frac{d\sigma_{(N)LO}}{dlogt} + \frac{d\sigma_{NLL}}{dlogt} - \frac{d\sigma_{NLL,\alpha_s}}{dlogt}\right]$$

Matched end-point:

$$log\frac{1}{t} \rightarrow log\left(\frac{1}{t} - \frac{1}{t_{max}} + \frac{e^{Bq}}{4}\right)$$

$$with\ t_{all} = 4e^{-Bq},\ \ t_{max} \sim 0.2$$

Result for (N)LO+NLL:



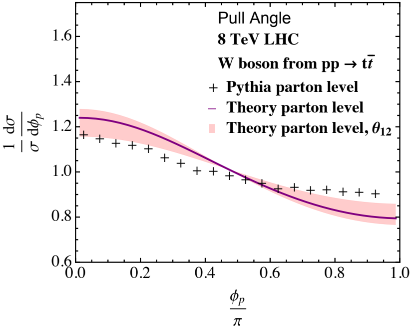
Backup: Sudakov factor at LL

The Sudakov factor at LL is

$$\Delta(t) = e^{-\frac{\alpha_s C_F}{2\pi} log^2 t}$$

And the Sudakov safe calculation becomes

$$\frac{d\sigma}{d\phi_p} = \int dt \Delta(t) \frac{d^2\sigma}{dtd\phi_p} \sim O(\sqrt{\alpha_s})$$



Sudakov safe calculation for LL Sudakov factor