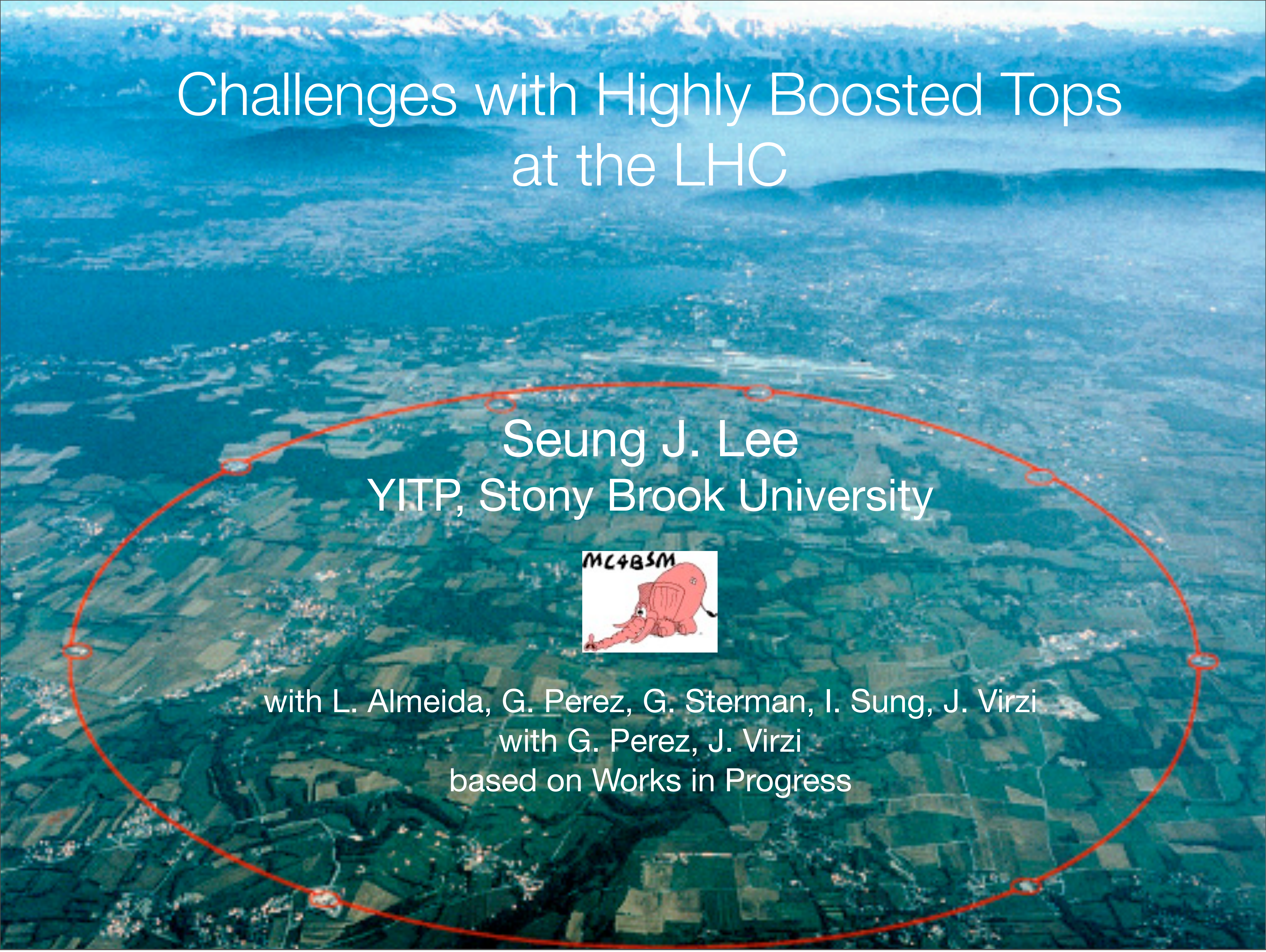


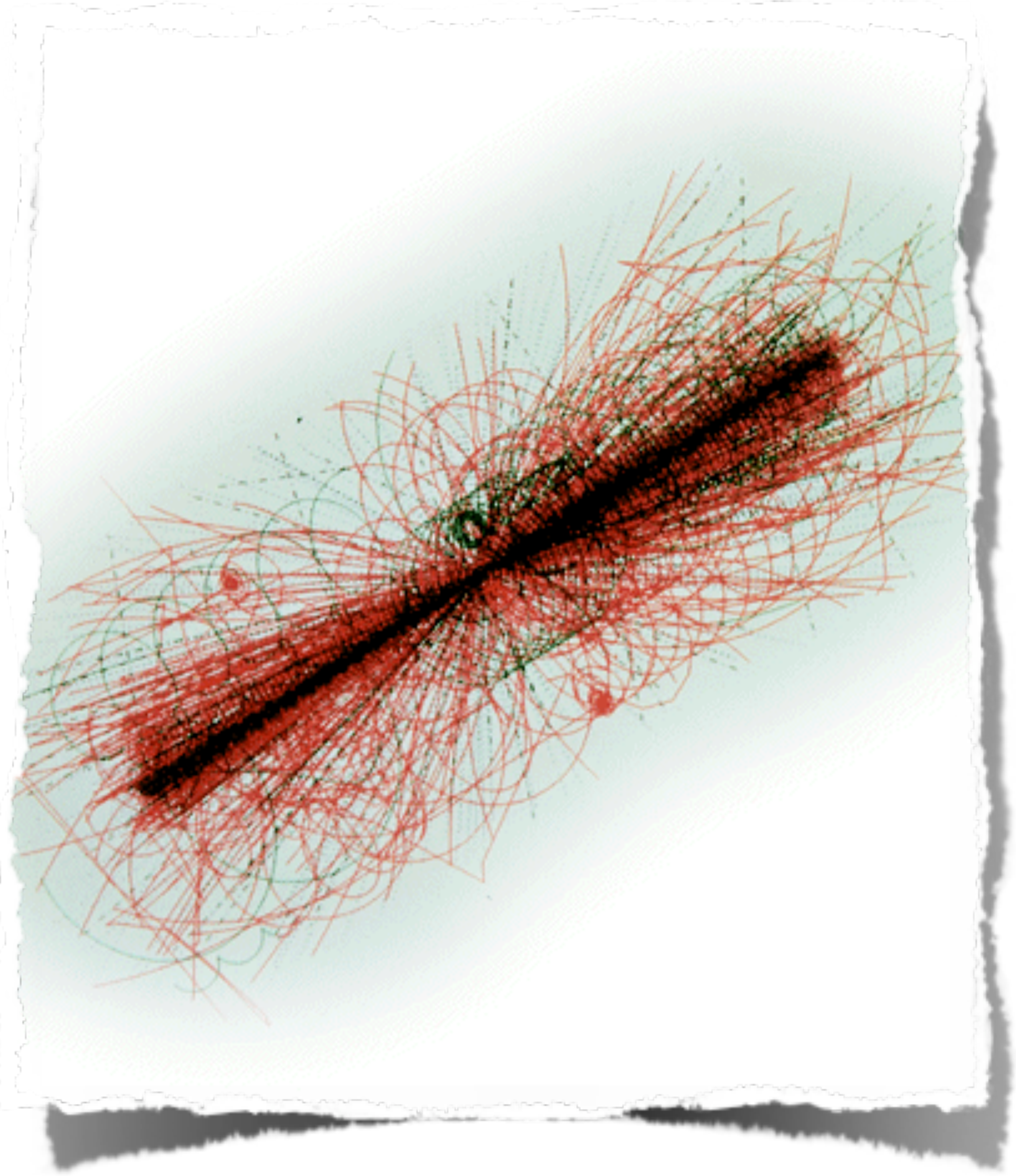
Challenges with Highly Boosted Tops at the LHC

Seung J. Lee
YITP, Stony Brook University

with L. Almeida, G. Perez, G. Sterman, I. Sung, J. Virzi
with G. Perez, J. Virzi
based on Works in Progress

Outline

- Highly Boosted Tops
- Highly Boosted QCD Jets
- Highly Boosted Top Pair Production
- Top Quark Polarization
- Summary



Highly Boosted Tops

- Interested in highly boosted tops from s-channel decay (for New Physics): $\mathrm{pp} \rightarrow X \rightarrow t\,\bar{t}$ $\mathrm{pp} \rightarrow X \rightarrow t\,Y$
- Focus mostly on the hadronic top (BR = 2/3) $t \rightarrow b\,W \rightarrow b\,j\,j$
- Challenges: decay products of highly boosted top will be highly collimated (high P_T = small ΔR): $\Delta R \sim 2\, m_t/P_T$
  - For $\Delta R < R_{min} \sim 0.4$, cannot distinguish individual jets

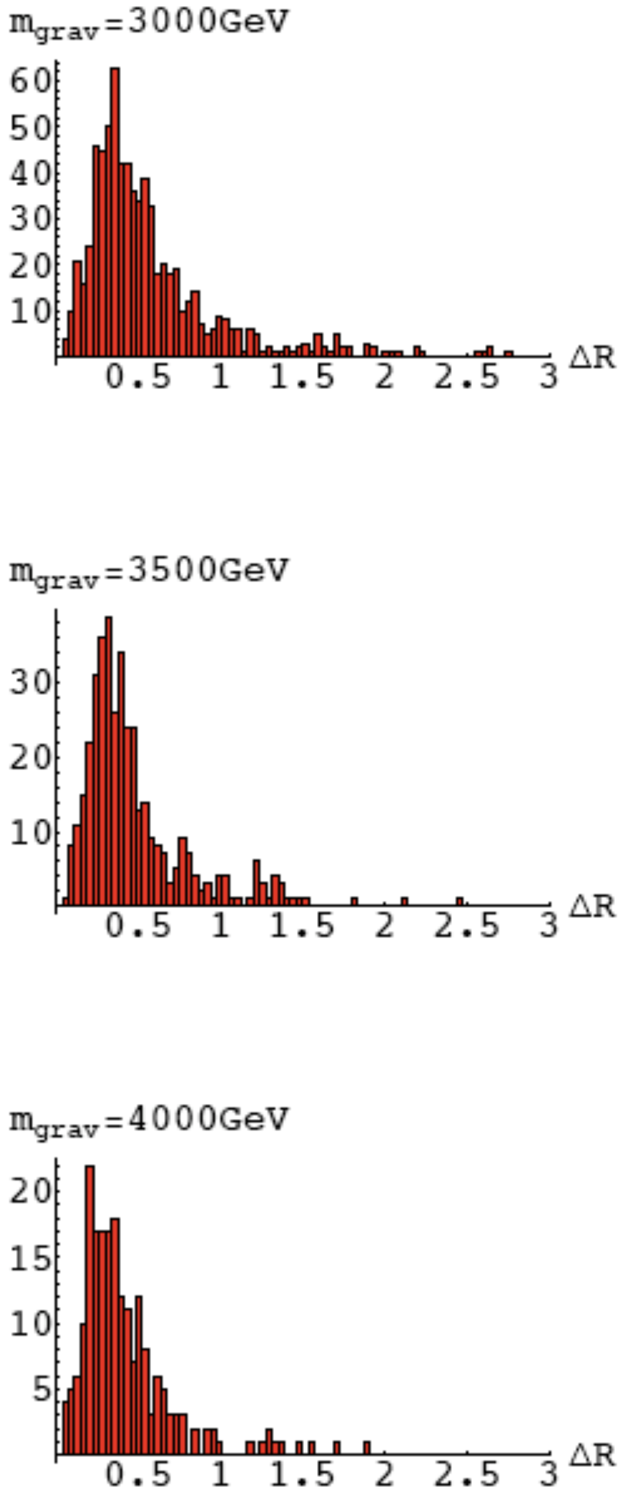
    (hadronic calorimeter cell size : $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$)

Highly Boosted Tops

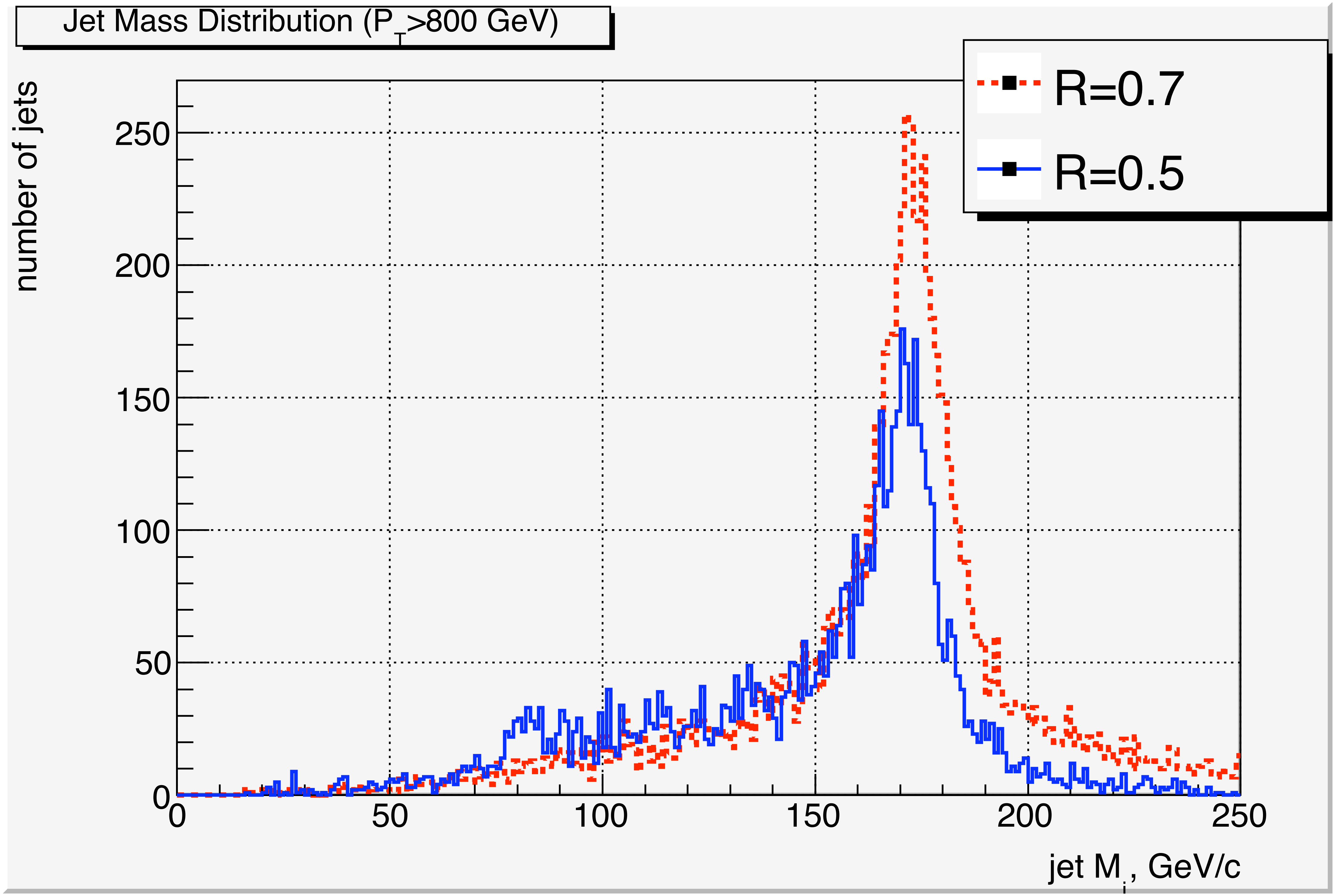
K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez, J. Virz

L. Fitzpatrick, J. Kaplan, L. Randall, L. Wang

- ΔR decreases as p_T increases
- For Small ΔR:
  - Usual criteria for top-tagging no longer work! (reconstructing W, then obtaining top)
  - Can we us a single Jet Mass to identify top?



MadGraph => pythia => pgs
(MLM)



Highly boosted hadronic top quarks

MC generation

Highly Boosted Top Quarks

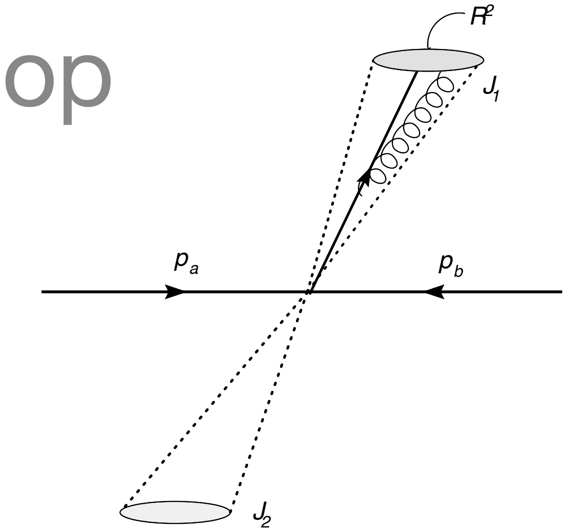
- b-tagging efficiency for highly boosted tops is wired (small ~20%) L. March, E. Ros, B. Salvachúa

  L. March, E. Ros, S. G. d.l. Hoz

- top quark radiation is another problem for top-jet mass distribution
  - not implemented in LO MC tools
  - order one effect $\sim \alpha_s \log^2(\frac{P_T}{m_T})$
- Jet-broadening at the detector level is also important
- Choosing an optimal cone size can be biased for parity-violating top production: (see later)

Highly Boosted QCD Jets

- Typical background for the highly boosted top (or other partons)



- Factorization Theorem:

$$\frac{d\sigma}{dm_{J_1}^2 dm_{J_2}^2 \cdots} = \int_{p_T^{min}} f_a \otimes f_b \otimes d\hat{\sigma}(p_T, \cdots) \otimes J_1^{(c)}(m_{J_1}^2, p_T, \cdots) \otimes J_2^{(d)}(m_{J_2}^2, p_T, \cdots) \otimes S(\cdots)$$

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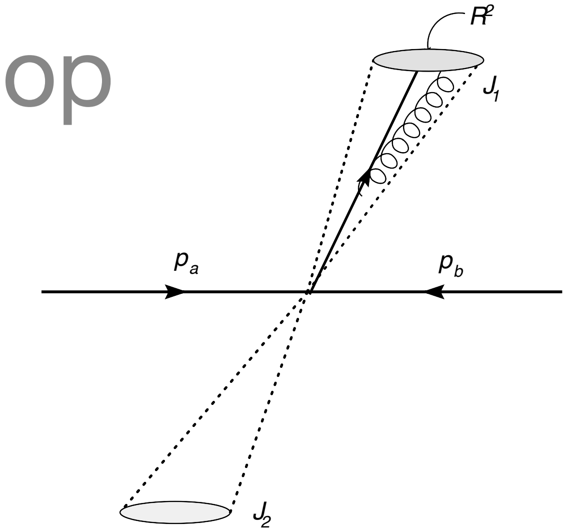

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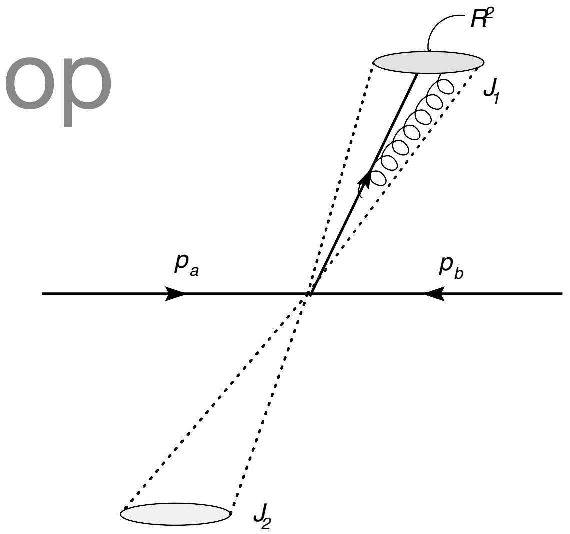

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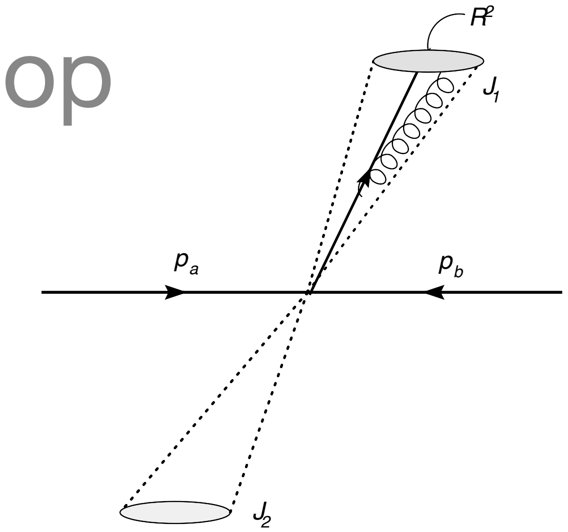

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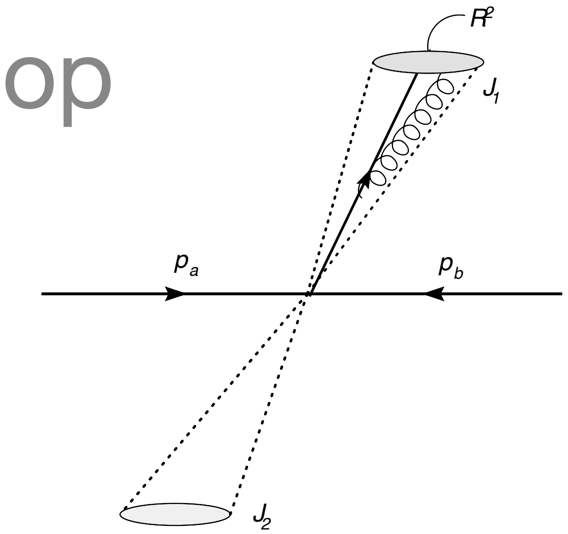

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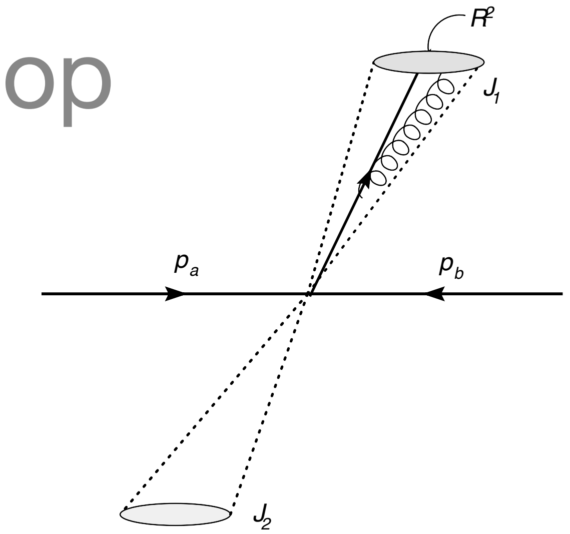

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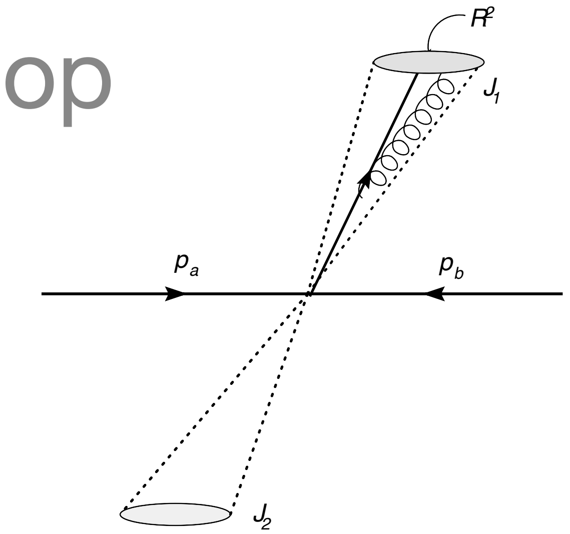

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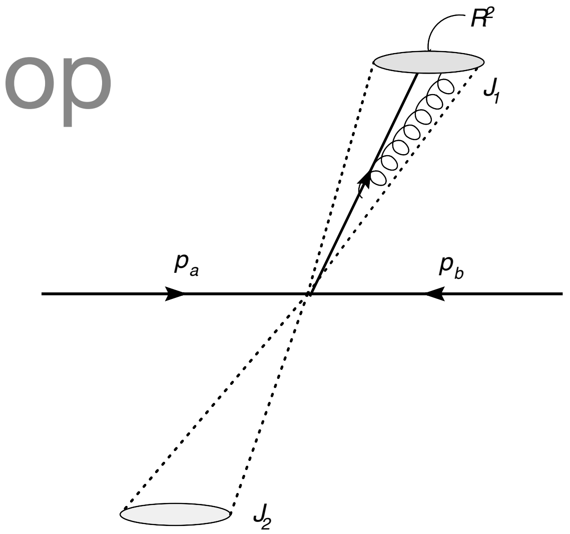

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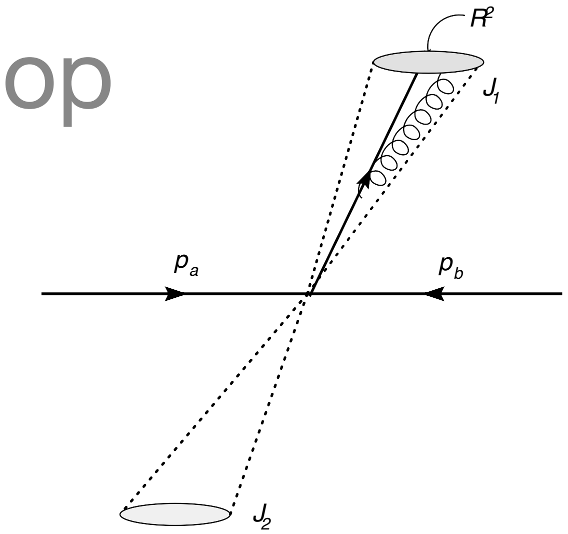

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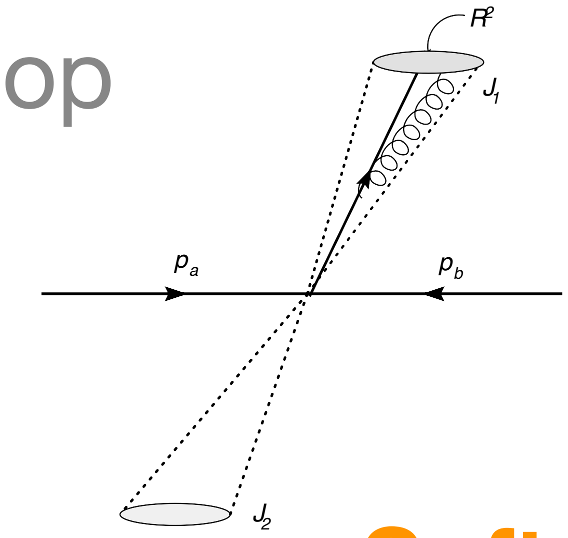

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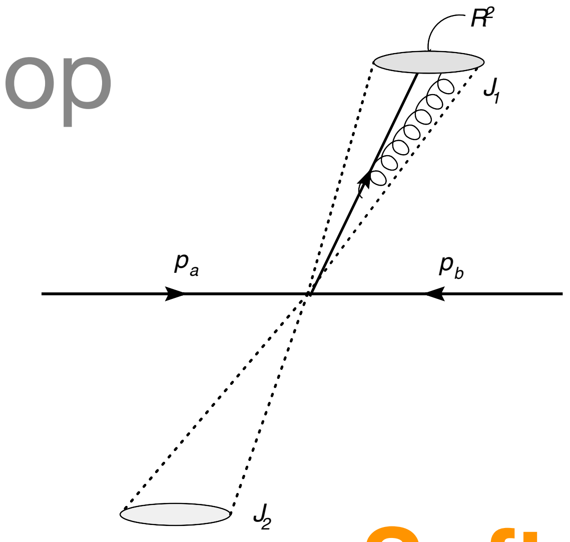

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→

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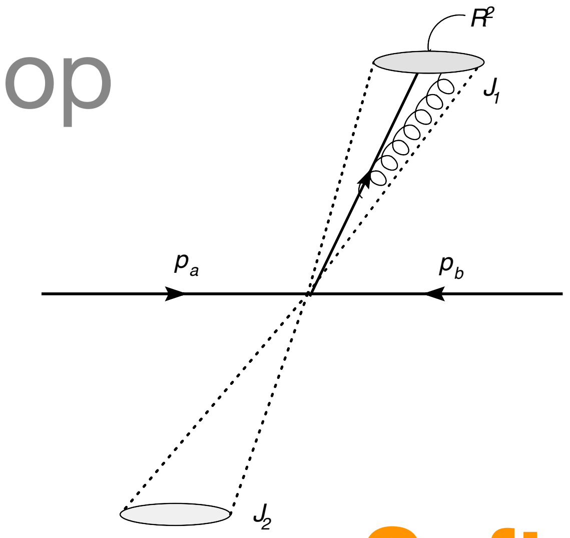

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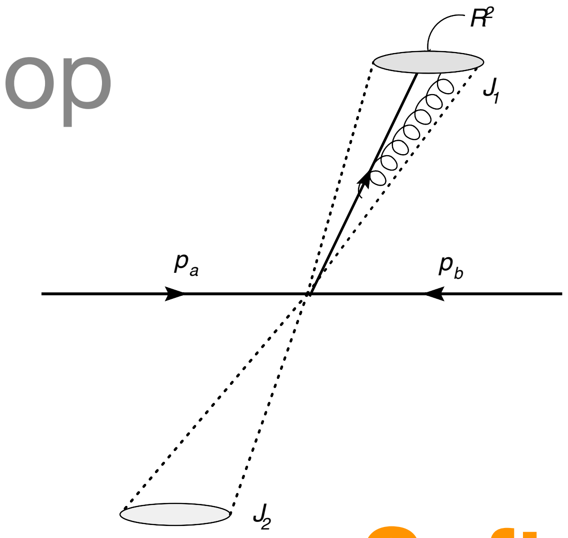

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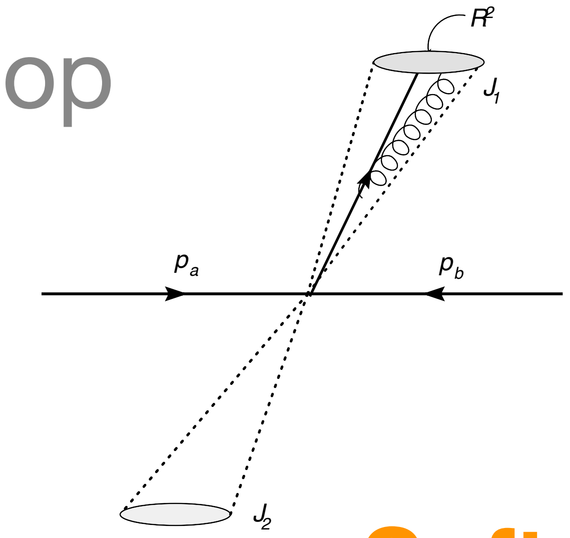

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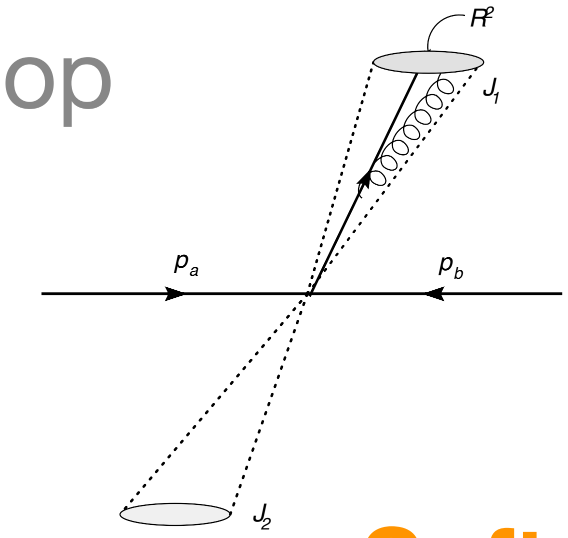

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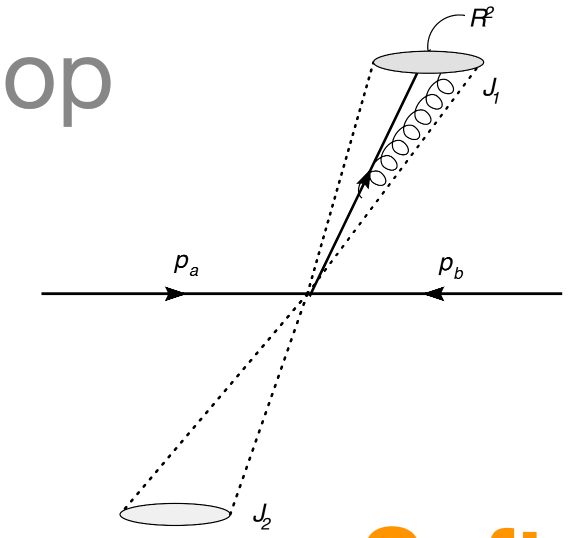

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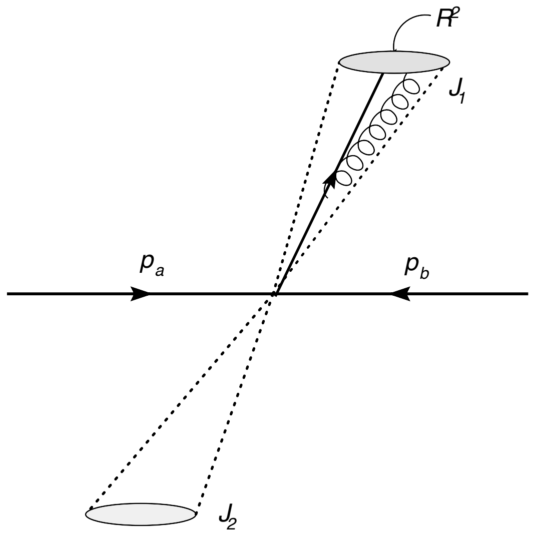
Highly Boosted QCD Jets

S. D. Ellis, J. Huston, K. Hatakeyama,
P. Loch, M. Tönnesmann

- Analytic Prediction:

$$\frac{1}{\sigma}\frac{d\sigma}{dm^2_{J_1}} = J_1^{Theory}$$



- Jet Function (for highly collimated jets: $R^2 < 1$)
  - **J** is a normalized probability (jet mass) distribution
  - **J** absorbs collinear enhancements to the outgoing particles in the underlying perturbative process

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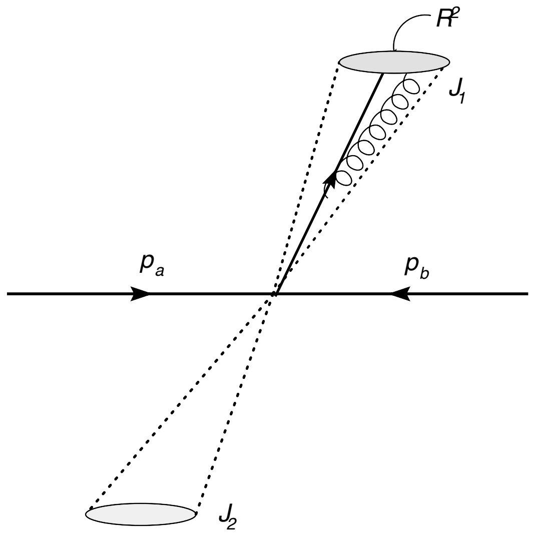

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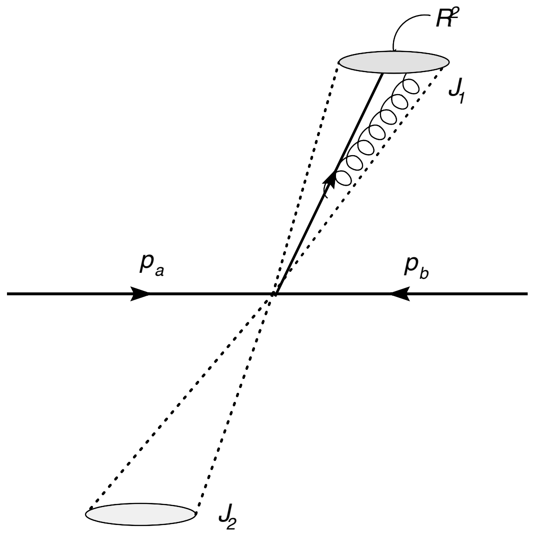

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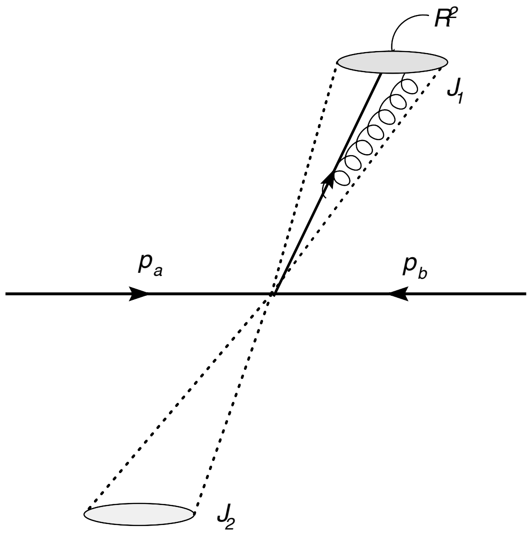

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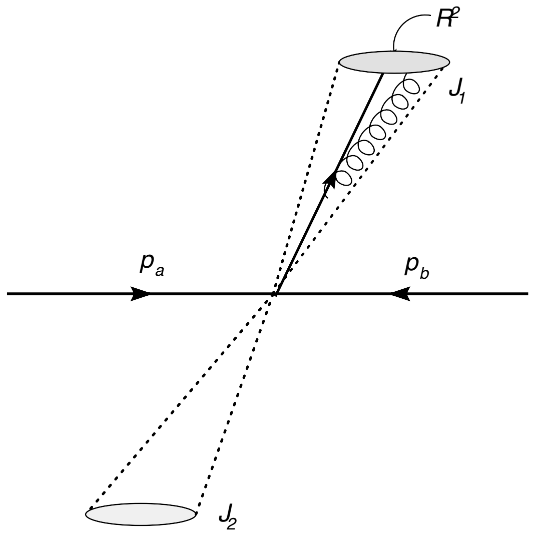

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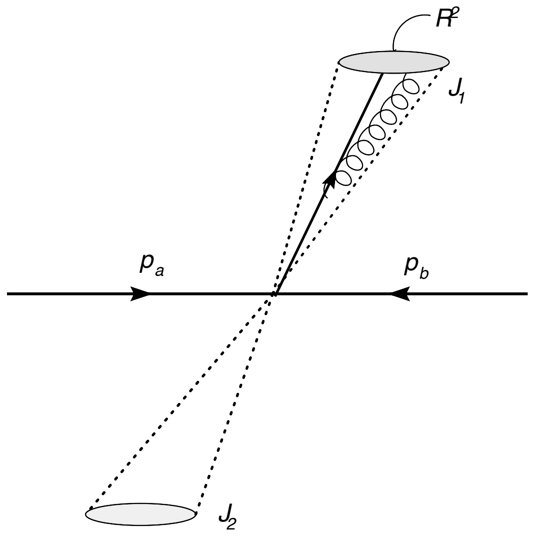

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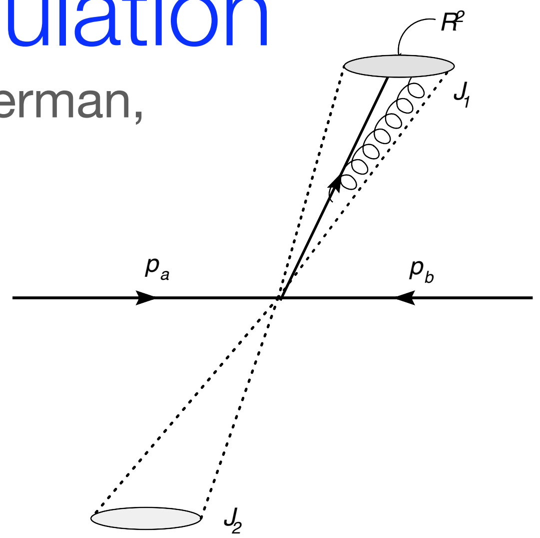
Perturbative Calculation

L. Almeida, G. Perez, SL, G. Sterman,
I. Sung, J. Virzi



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Highly Boosted QCD Jets

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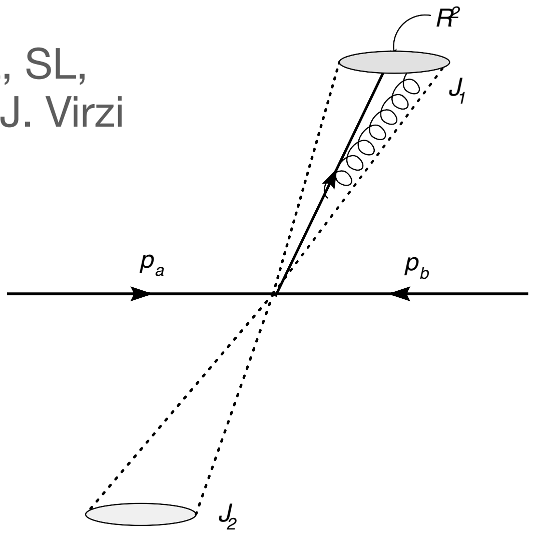
- At Leading Log order, our result is: L. Almeida, G. Perez, SL, G. Sterman, I. Sung, J. Virzi



$$J_1^{(c)}(m_{J_1}^2, p_T, R^2)$$
$$= -\alpha_{\rm S}(p_T)\frac{1}{m_{J_1}^2}\frac{C_{(c)}}{\pi}\log\left(\frac{m_J^2}{R^2\,p_T^2}\right)\exp\left\{-\alpha_{\rm S}\frac{C_{(c)}}{2\,\pi}\log^2\left(\frac{m_J^2}{R^2\,p_T^2}\right)\right\}$$

Highly Boosted QCD Jets

S. D. Ellis, J. Huston, K. Hatakeyama,
P. Loch, M. Tönnesmann

- At Leading Log order, our result is:

L. Almeida, G. Perez, SL,
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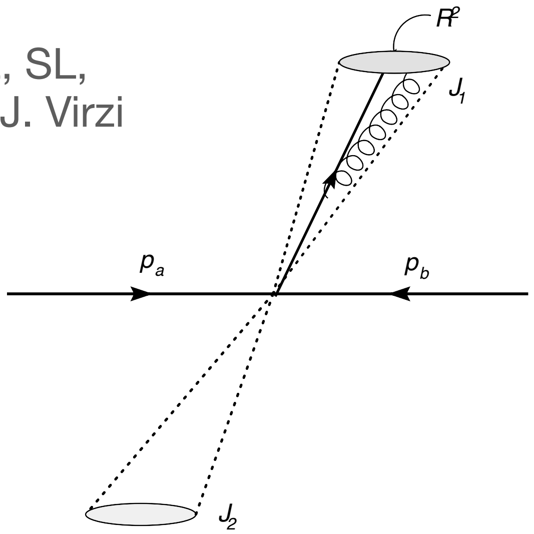

$$
\begin{aligned}
&J_1^{(c)}(m_{J_1}^2, p_T, R^2) \\
&= -\alpha_{\mathrm{S}}(p_T)\frac{1}{m_{J_1}^2}\frac{C_{(c)}}{\pi}\log\left(\frac{m_J^2}{R^2\,p_T^2}\right)\exp\left\{-\alpha_{\mathrm{S}}\frac{C_{(c)}}{2\,\pi}\log^2\left(\frac{m_J^2}{R^2\,p_T^2}\right)\right\}
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$$

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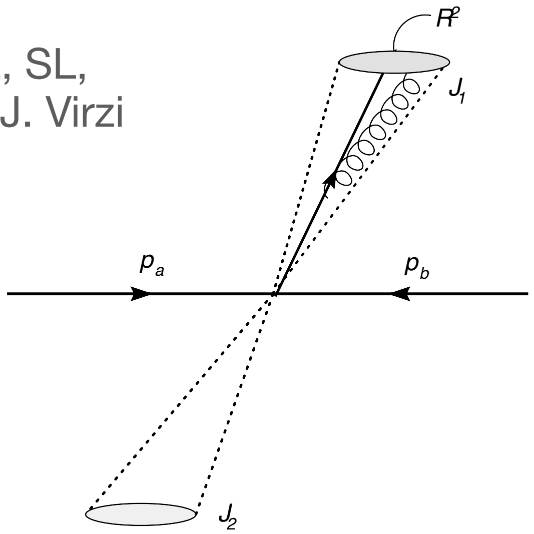

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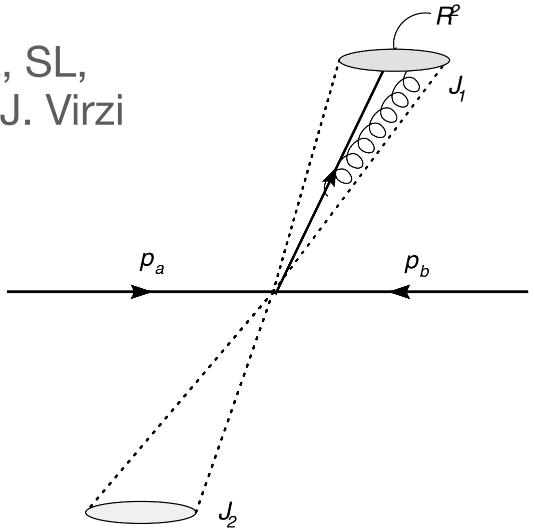

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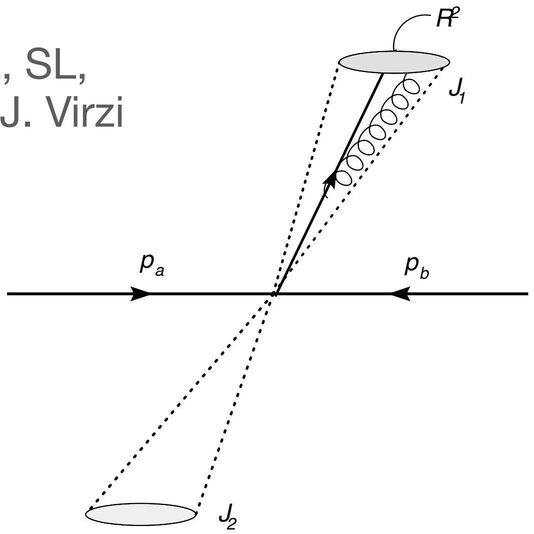

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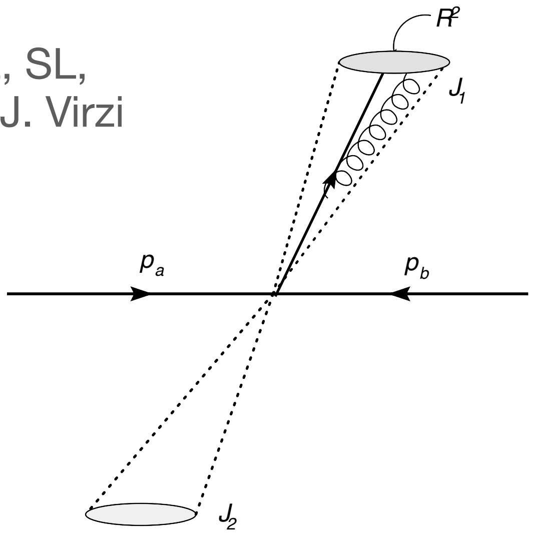

$$\boxed{\begin{aligned}&J_1^{(c)}(m_{J_1}^2, p_T, R^2)\\ &= \underbrace{-\alpha_S(p_T)\frac{1}{m_{J_1}^2}\frac{C_{(c)}}{\pi}\log\left(\frac{m_J^2}{R^2\,p_T^2}\right)}_{\text{NLO}}\underbrace{\exp\left\{-\alpha_S\frac{C_{(c)}}{2\,\pi}\log^2\left(\frac{m_J^2}{R^2\,p_T^2}\right)\right\}}_{\text{Resummation (LL)}}\end{aligned}}$$

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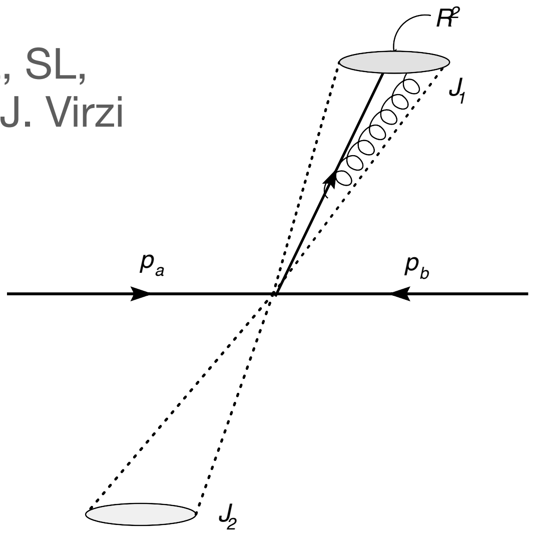

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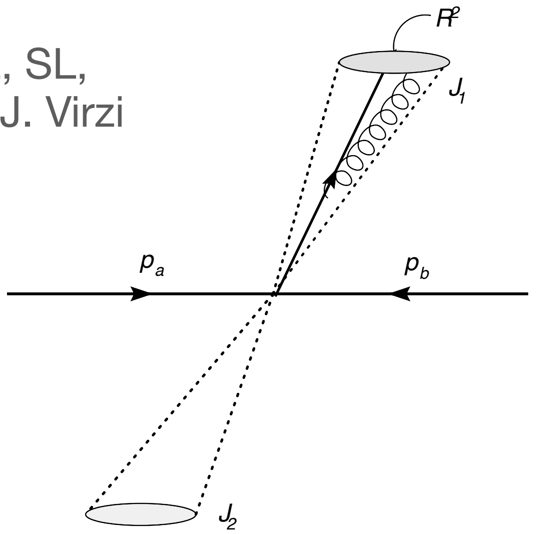

$$J_1^{(c)}(m^2_{J_1}, p_T, R^2) = \underbrace{-\alpha_S(p_T)\frac{1}{m^2_{J_1}}\frac{C_{(c)}}{\pi}\log\left(\frac{m^2_J}{R^2\,p^2_T}\right)}_{\text{NLO}}\underbrace{\exp\left\{-\alpha_S\frac{C_{(c)}}{2\,\pi}\log^2\left(\frac{m^2_J}{R^2\,p^2_T}\right)\right\}}_{\text{Resummation (LL)}}$$

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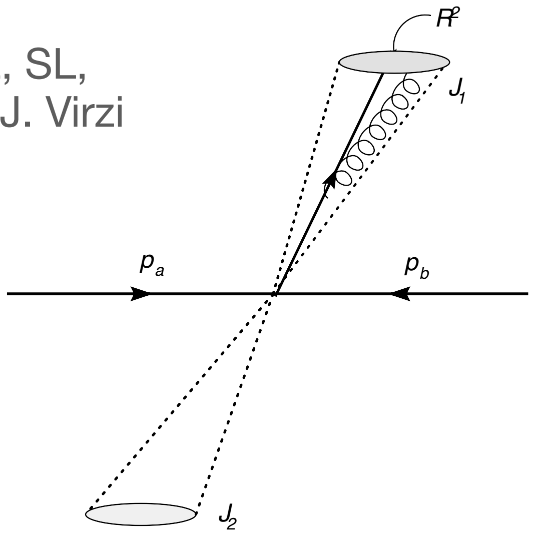

{ quark jets:
gluon jets:

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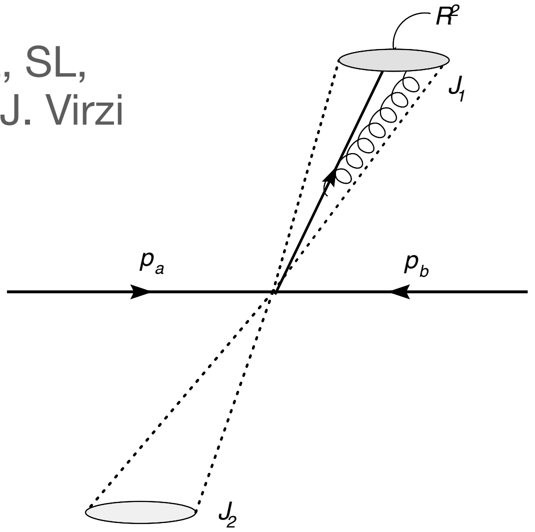

quark jets: $C_{(q)} = C_F = \frac{4}{3}$

gluon jets:

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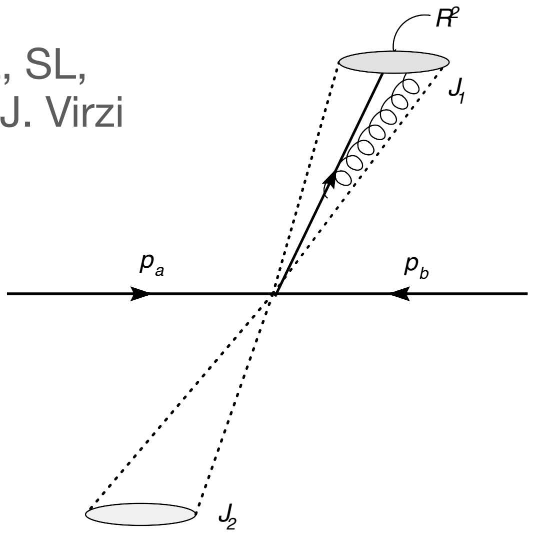

quark jets: $C_{(q)} = C_F = \frac{4}{3}$

gluon jets: $C_{(g)} = C_A = 3$

$$\boxed{J_1^{(c)}(m_{J_1}^2, p_T, R^2) = \underbrace{-\alpha_S(p_T)\frac{1}{m_{J_1}^2}\frac{C_{(c)}}{\pi}\log\left(\frac{m_J^2}{R^2\,p_T^2}\right)}_{\text{NLO}} \underbrace{\exp\left\{-\alpha_S\frac{C_{(c)}}{2\,\pi}\log^2\left(\frac{m_J^2}{R^2\,p_T^2}\right)\right\}}_{\text{Resummation (LL)}}}$$

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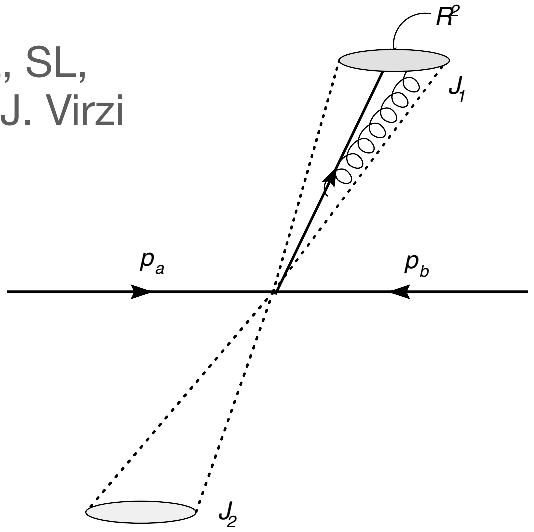

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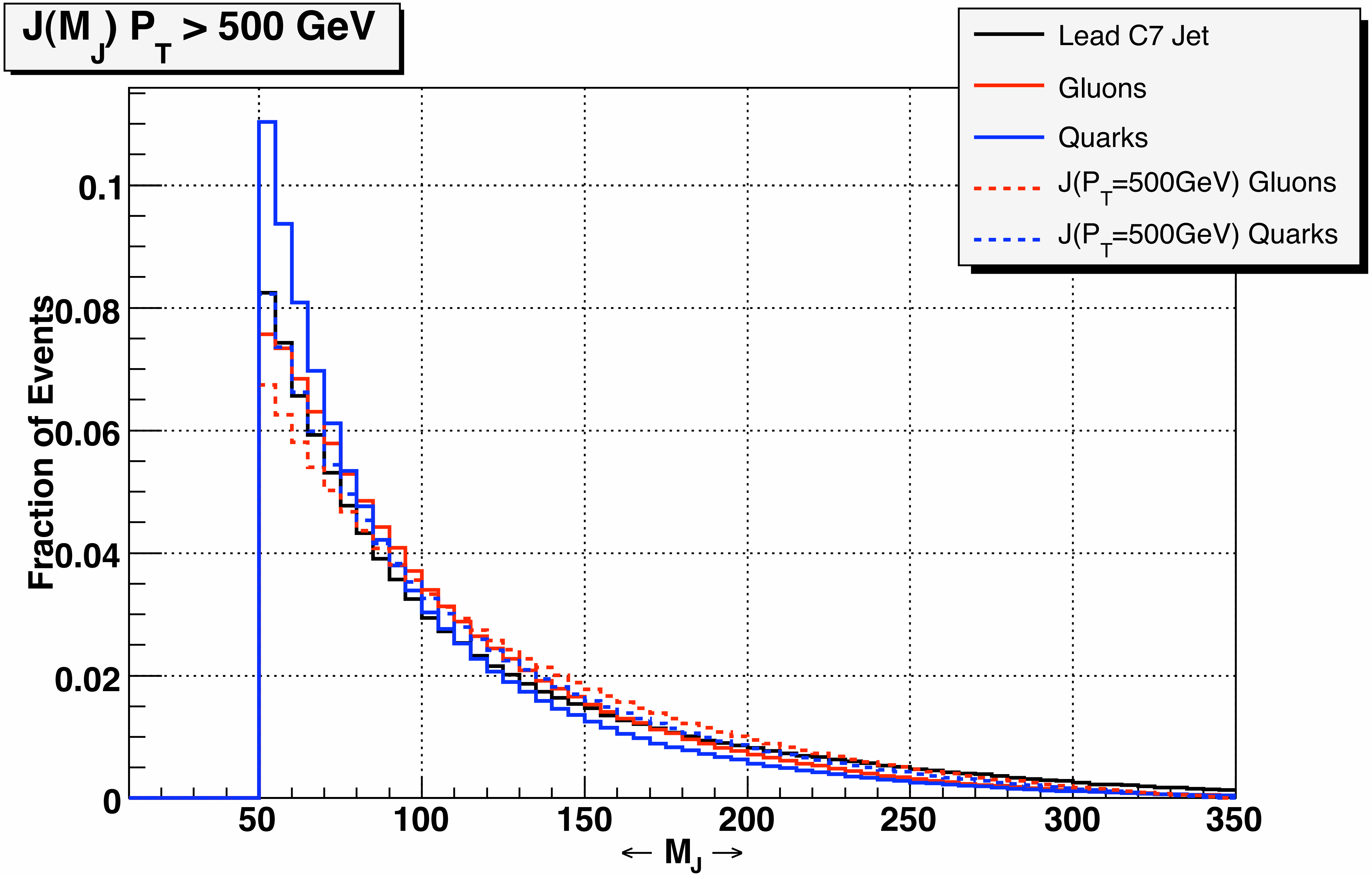
- Note that at low order, jet function has no dependency on pseudo-rapidity

Highly Boosted QCD Jets

- With a Mass Cut (50 GeV)

Sherpa (CKKW)
Without Detector
Simulation



Highly Boosted QCD Jets

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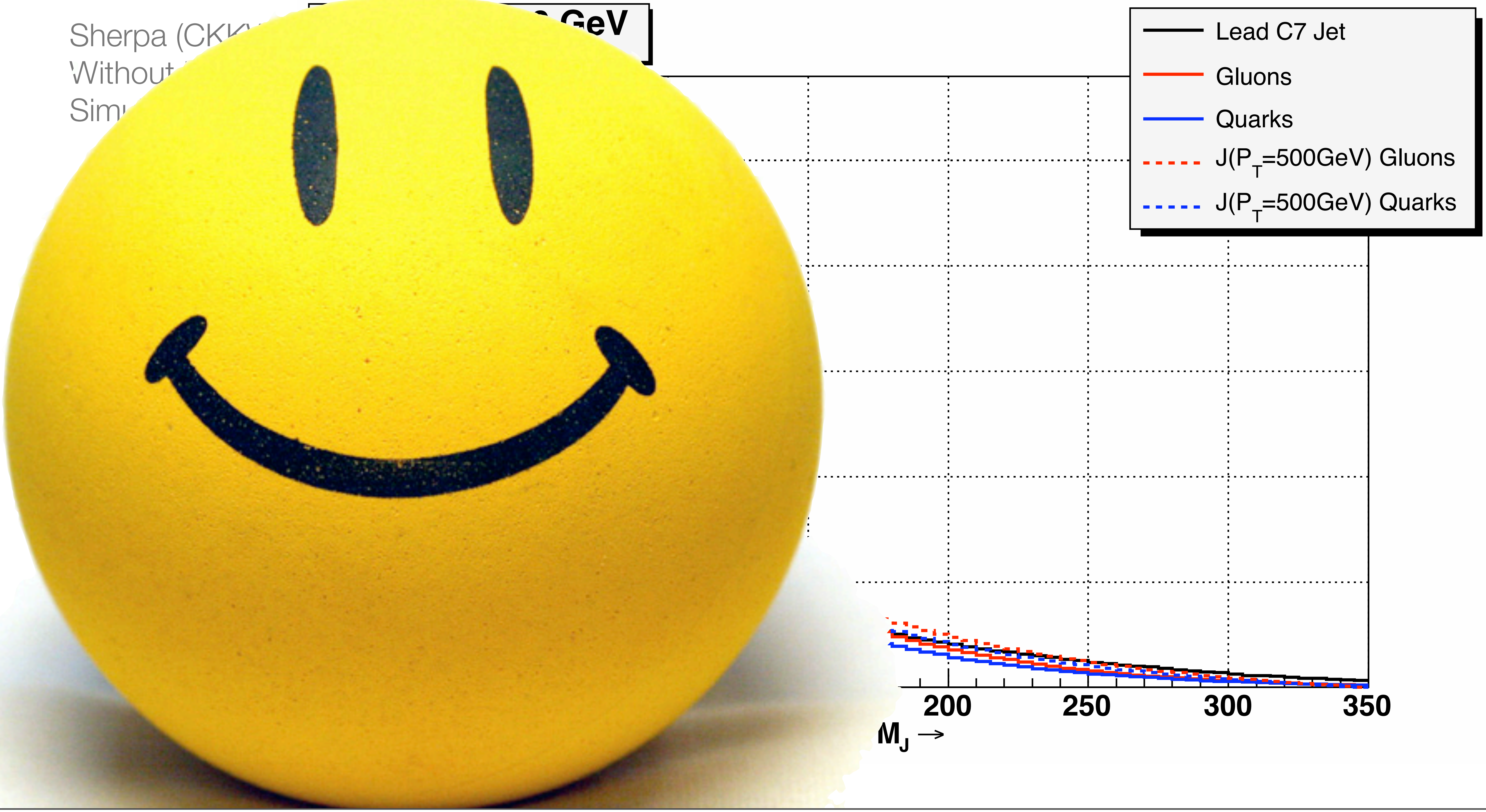
Sherpa (CKK

Without

Sim



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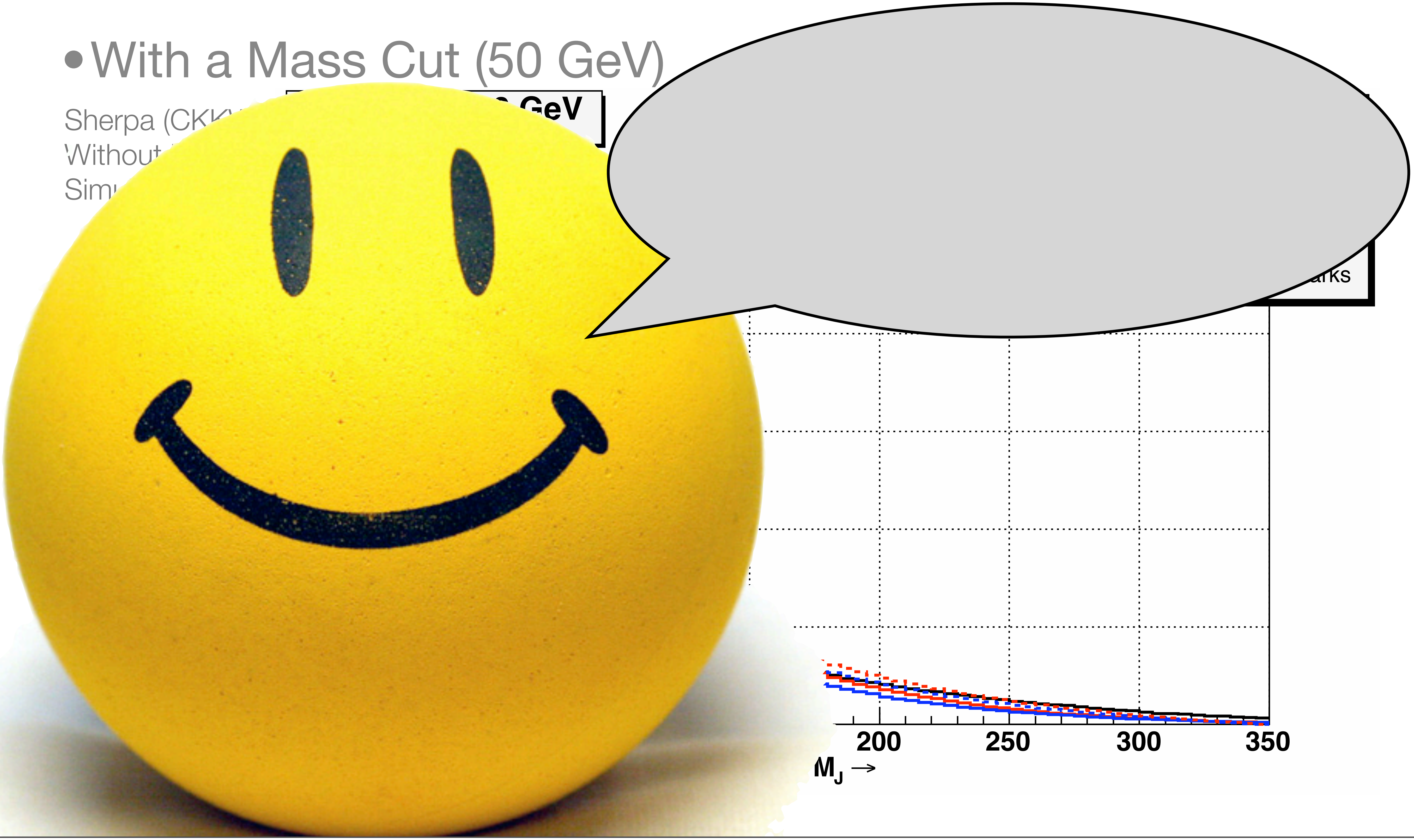

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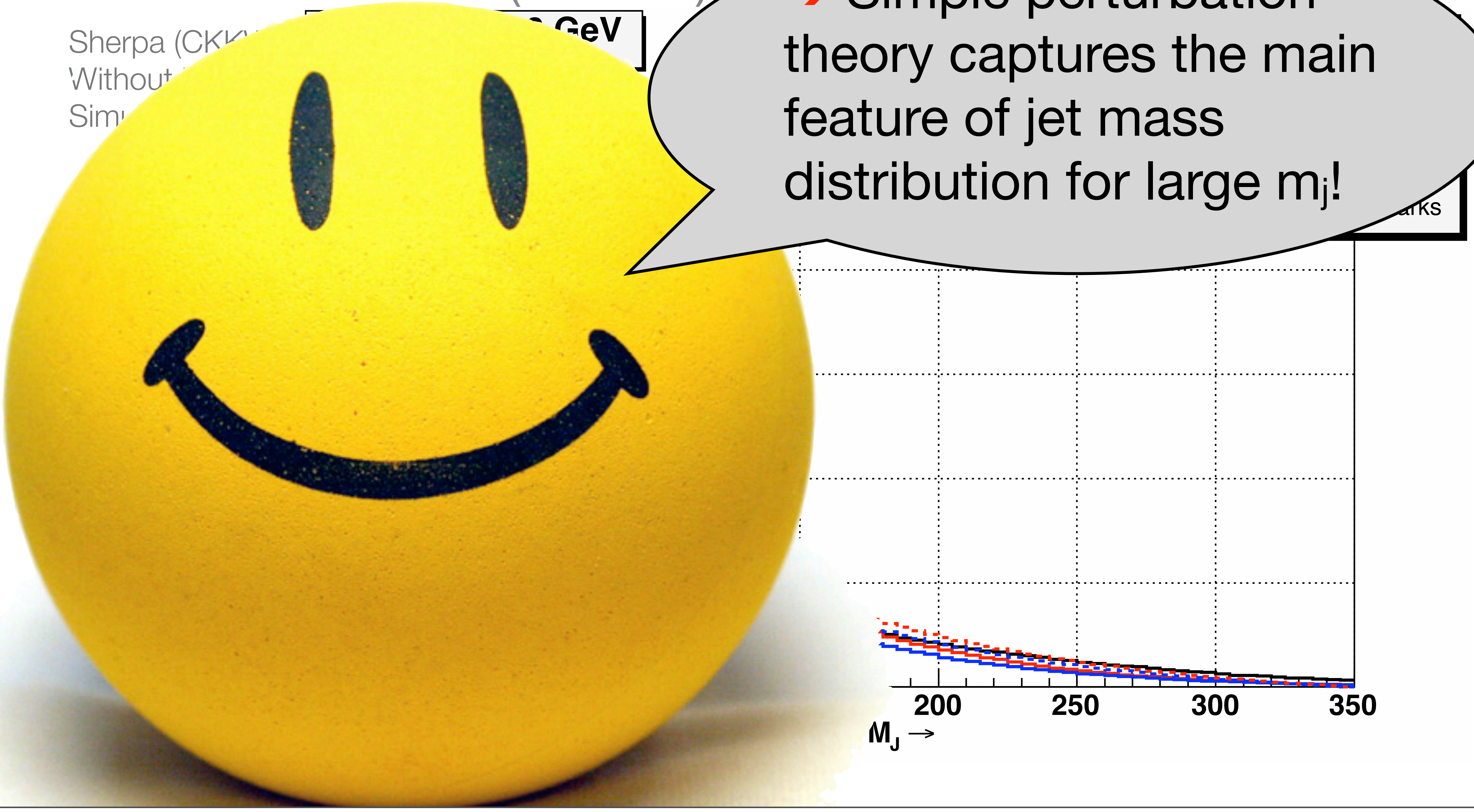
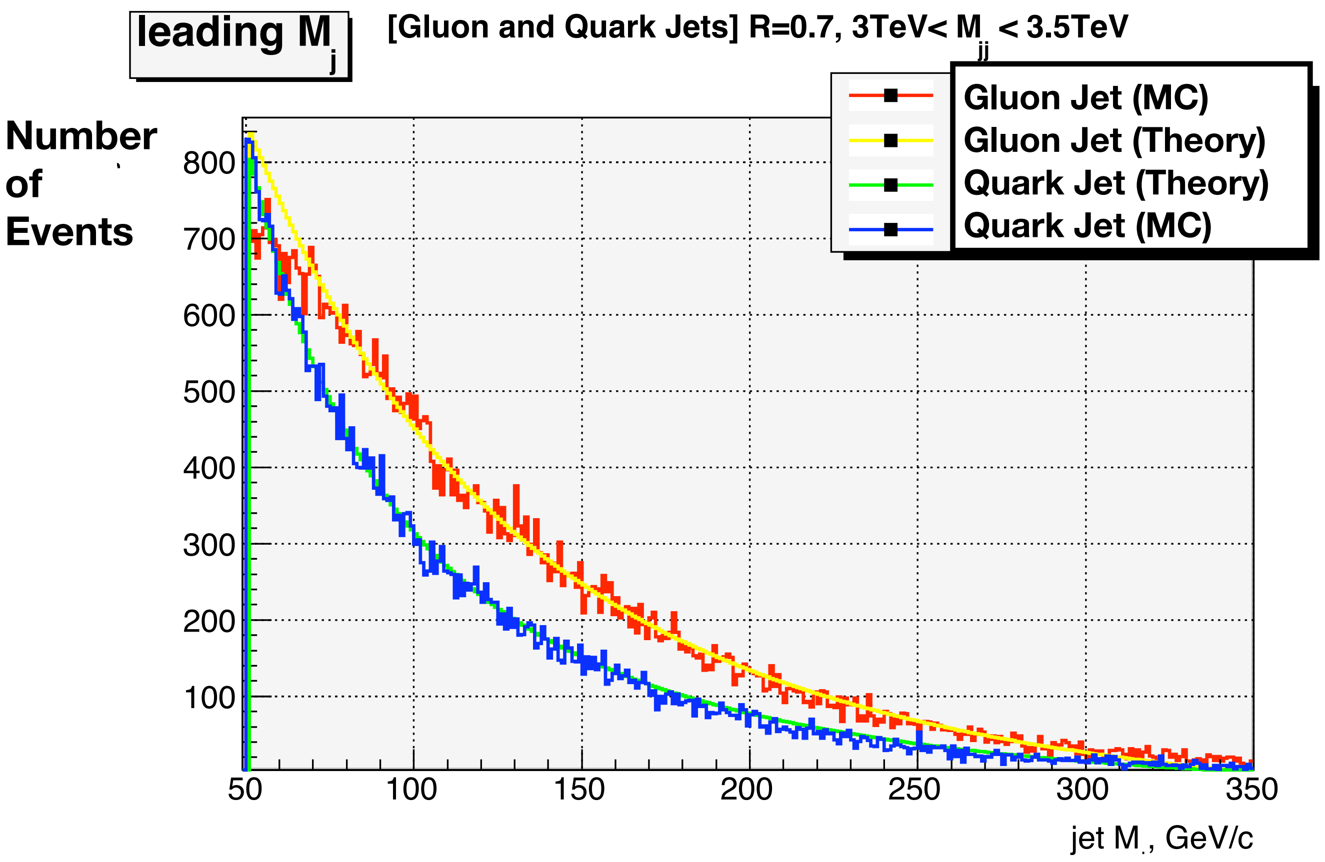


→ Simple perturbation theory captures the main feature of jet mass distribution for large m_j!

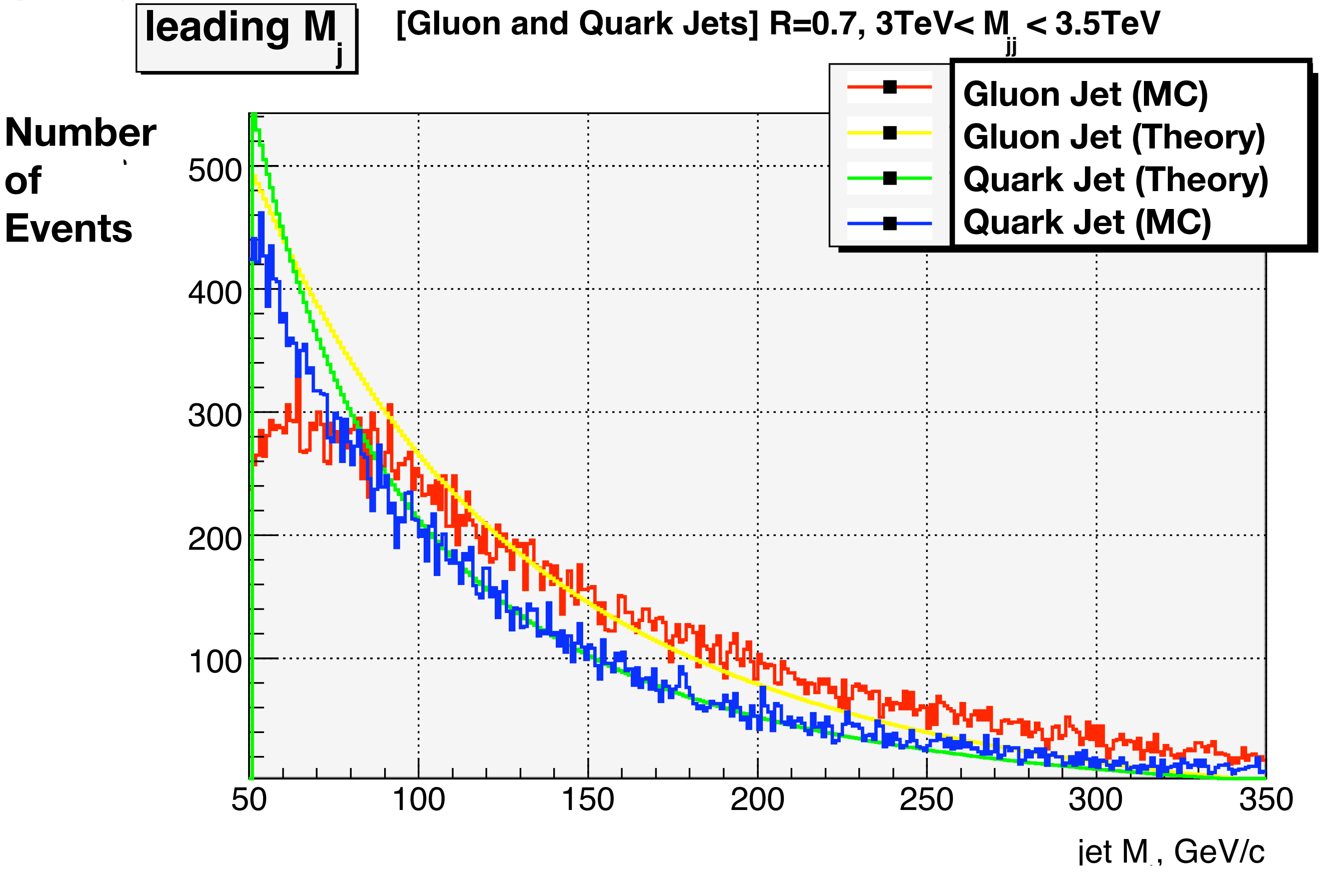
Highly Boosted QCD Jets

MadGraph => pythia => pgs
(MLM)

- For Jet mass distribution, pseudo-rapidity dependence is negligible
- For new physics or any non-QCD physics, expect a strong pseudo-rapidity dependence



cone size: R=0.7
$P_T > 1000$ GeV, $0.5 < \eta < 1.0$

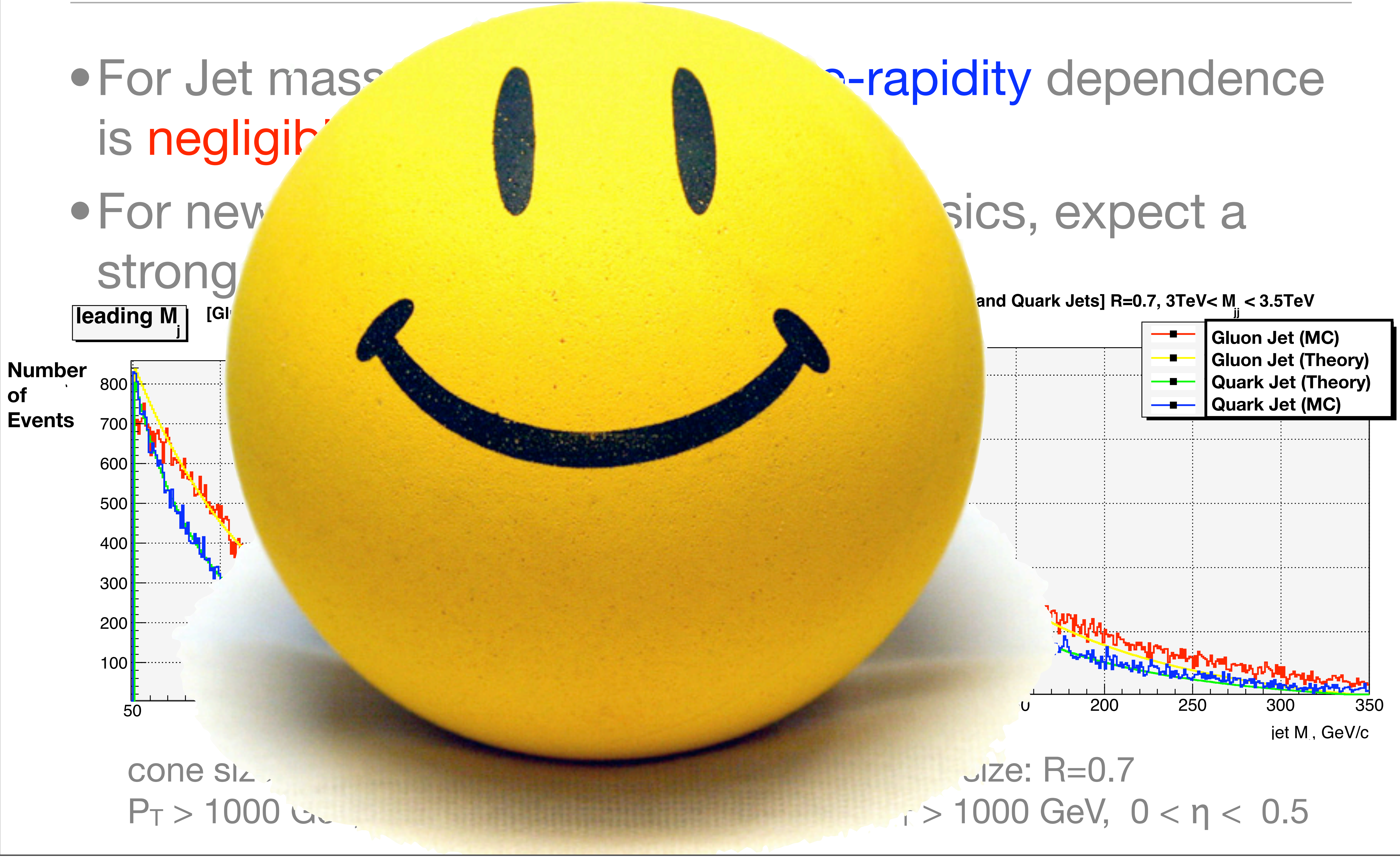


cone size: R=0.7
$P_T > 1000$ GeV, $0 < \eta < 0.5$

Highly Boosted QCD Jets

MadGraph => pythia => pgs
(MLM)

- For Jet mass -rapidity dependence is negligib
- For new sics, expect a strong



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Highly Boosted QCD Jets

MadGraph => pythia => pgs
(MLM)

- For Jet mass
  is **negligib**
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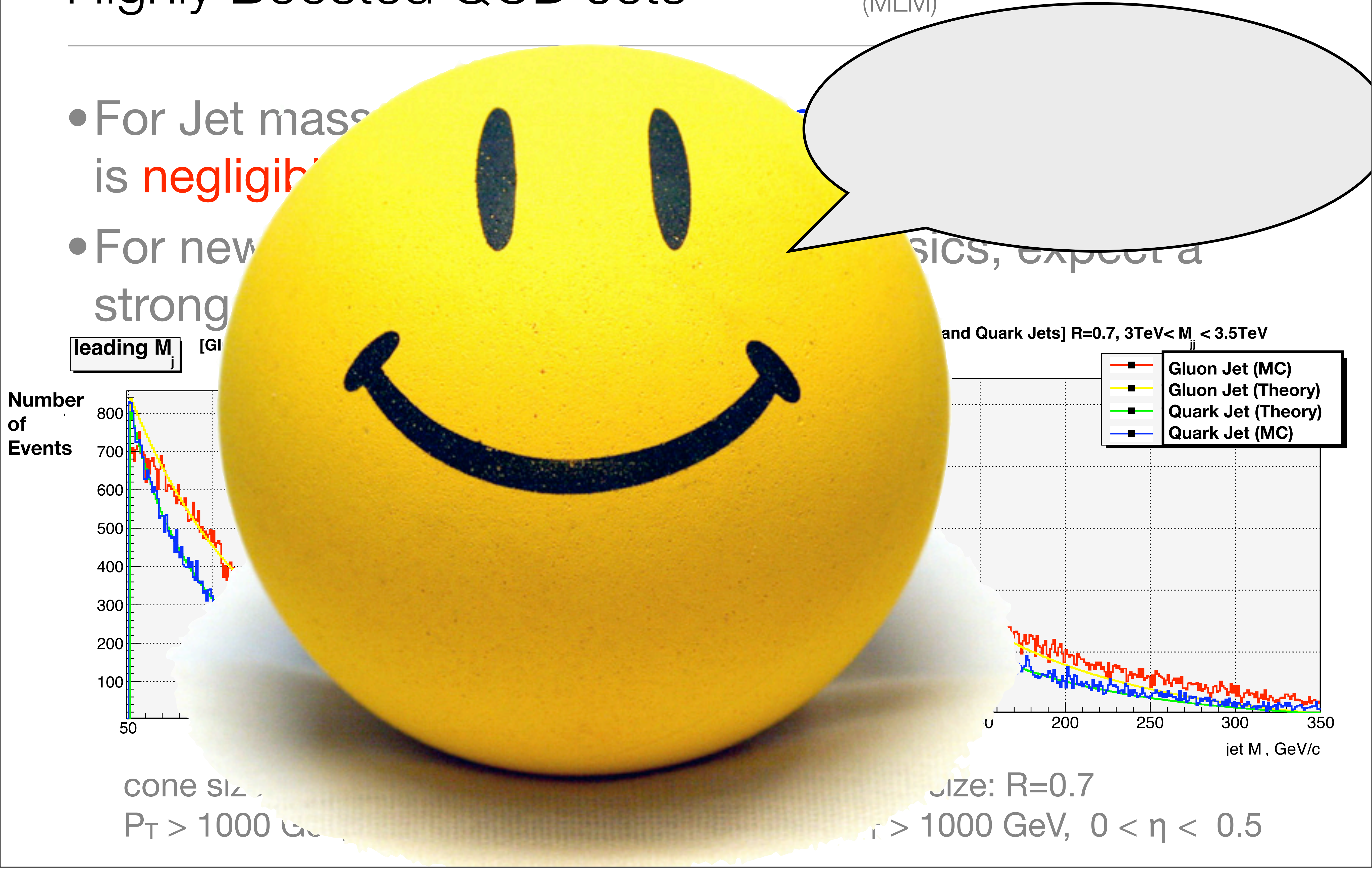

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Highly Boosted QCD Jets

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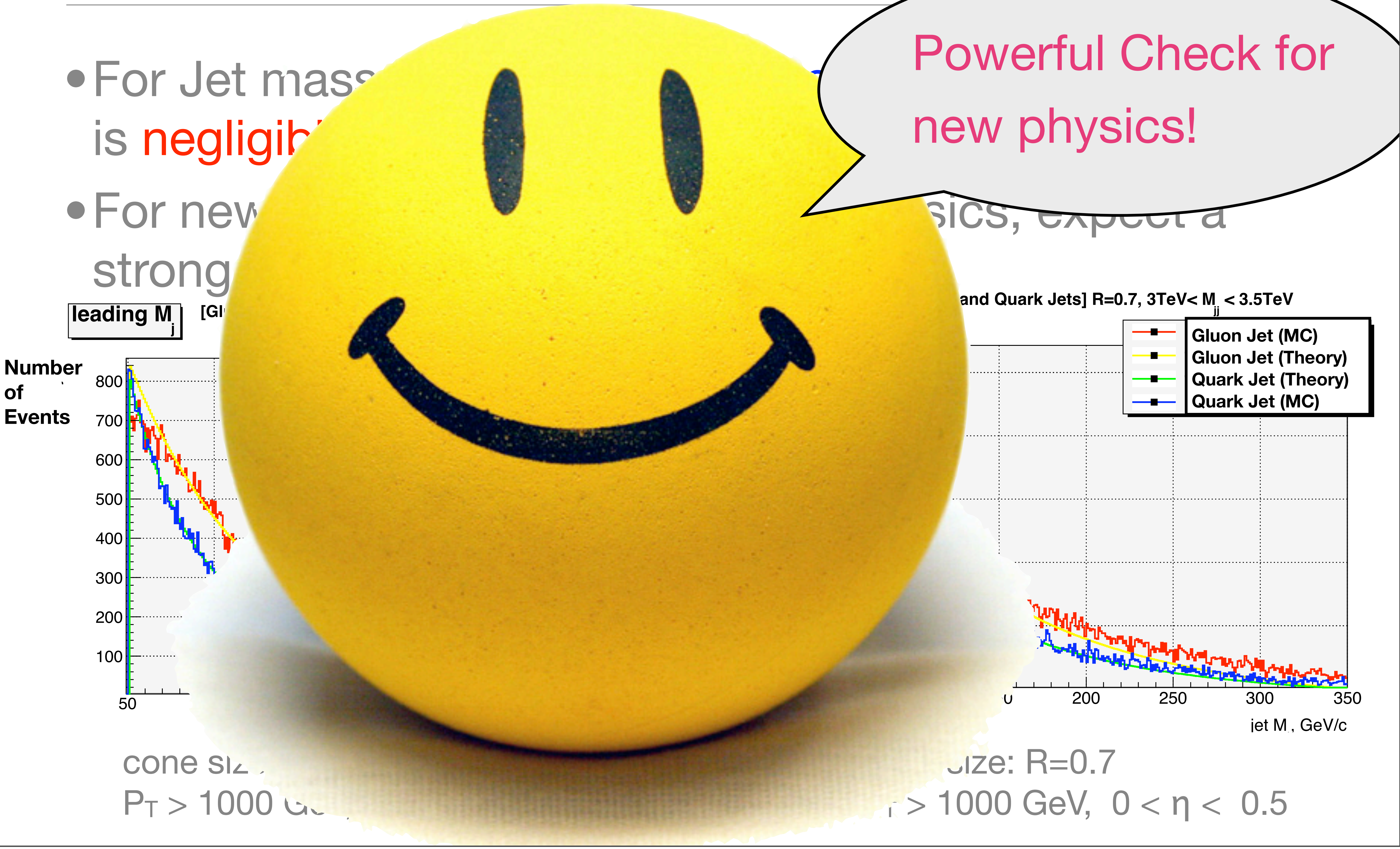


Powerful Check for new physics!

cone siz ize: R=0.7

P_T > 1000 G T > 1000 GeV, 0 < η < 0.5

Highly Boosted Top Pair Production

W. Skiba and David Tucker-Smith
U. Baur and L.H. Orr
R. Frederix and F. Maltoni

- Important discovery channel for new physics:

$$pp \to X \to t\bar{t}$$

- Focus on all-hadronic mode (~40%):

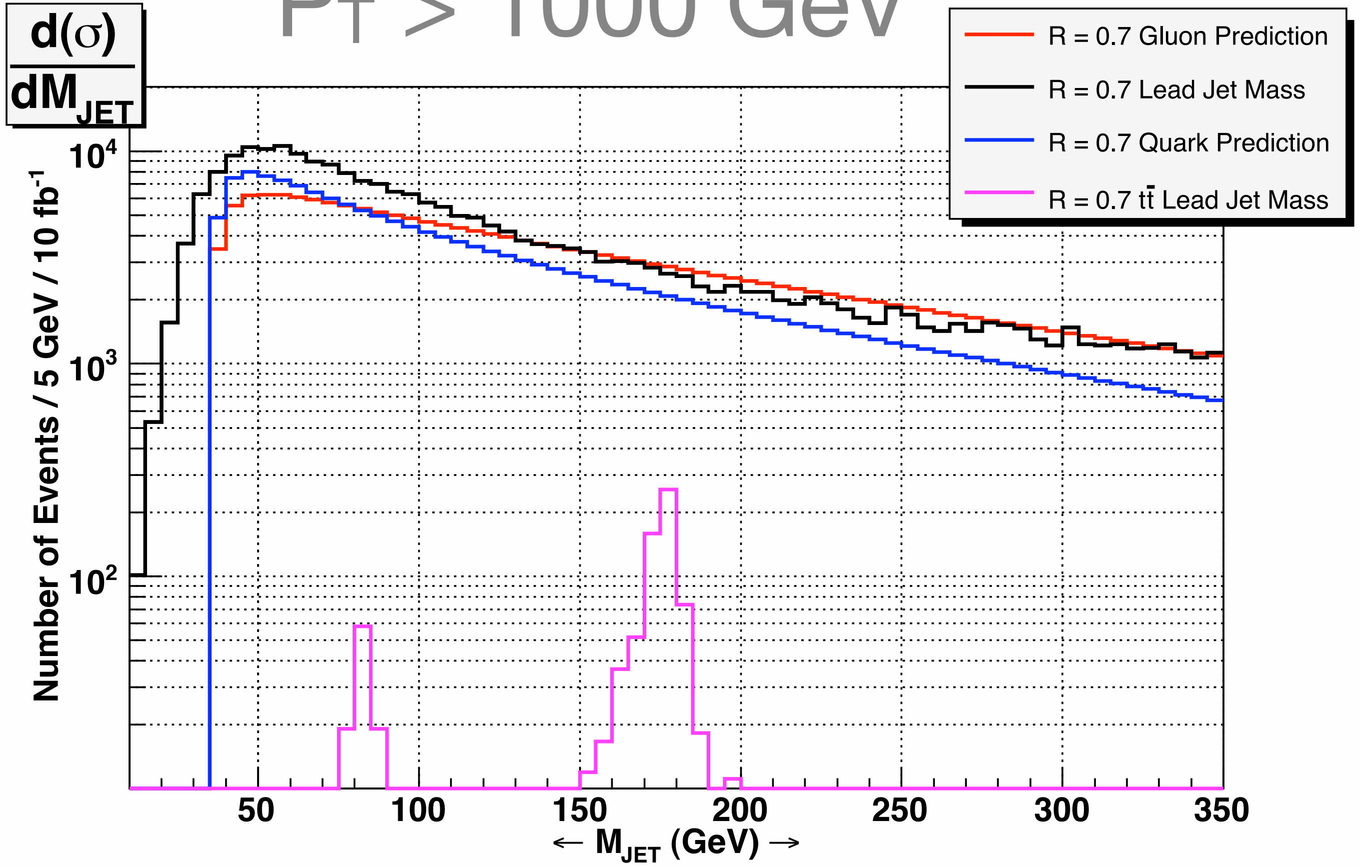
$$t\bar{t} \to WWb\bar{b} \to j_1j_2j_3j_4b\bar{b}$$

- Decay products are highly collimated
- Examine top-tagging by single jet mass
- Dominant background is the QCD dijet

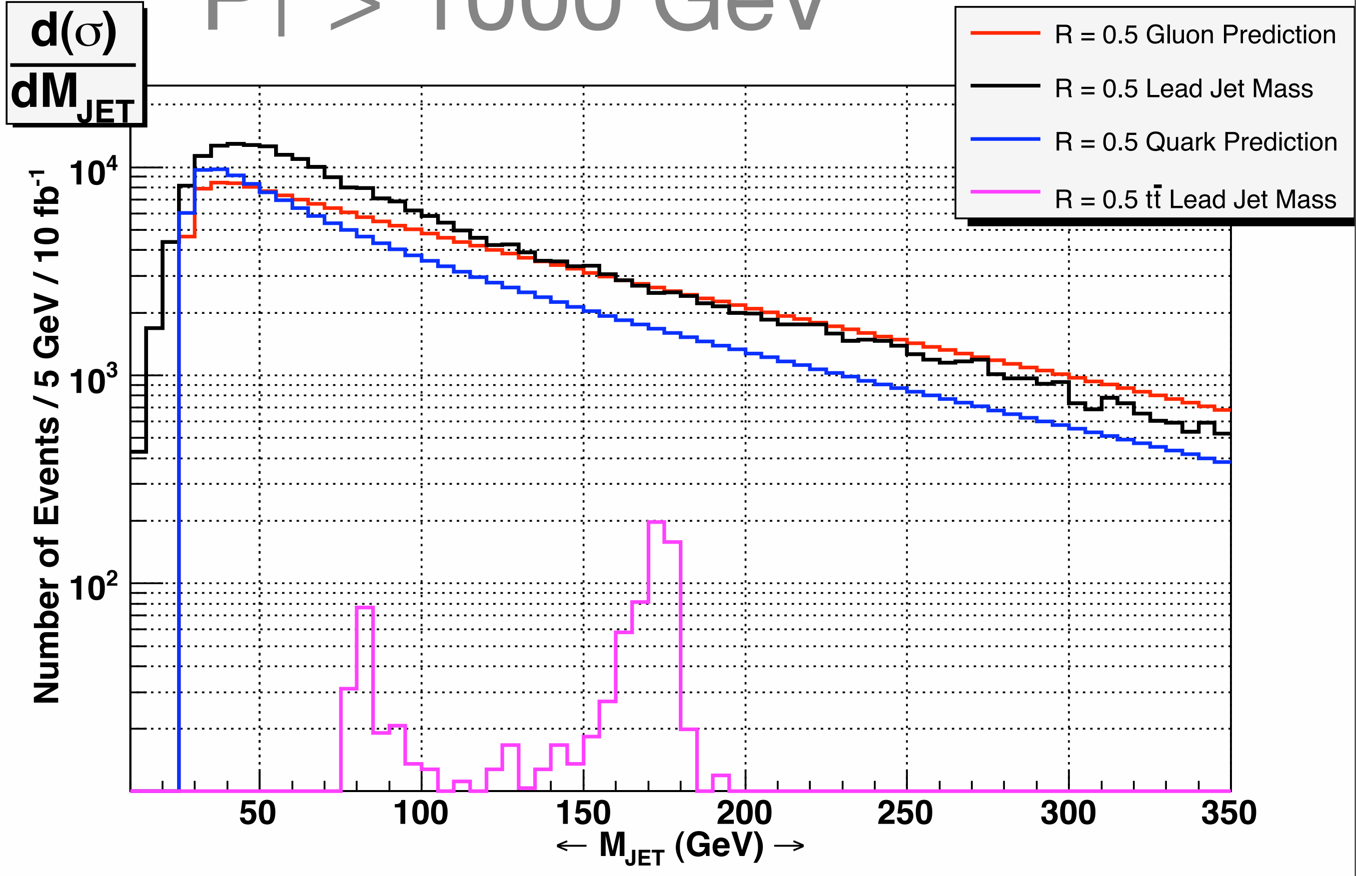
Without Detector Simulation

Sherpa (CKKW)
Without Detector
Simulation

cone size: R=0.7
P_T > 1000 GeV



cone size: R=0.5
P_T > 1000 GeV



- Signal(SM top) to background(QCD jet) ratio, before b-tagging: S/B~1/65
- One b-tagging is not enough: Need two to get S/B~6

(with b-tagging efficiency ~20% and fake-b-tagging rate ~1%)

L. March, E. Ros, B. Salvachúa ATL-Phys-PUB-2006-002

Highly Boosted top quark pair against QCD dijet

Highly Boosted Top Pair Production

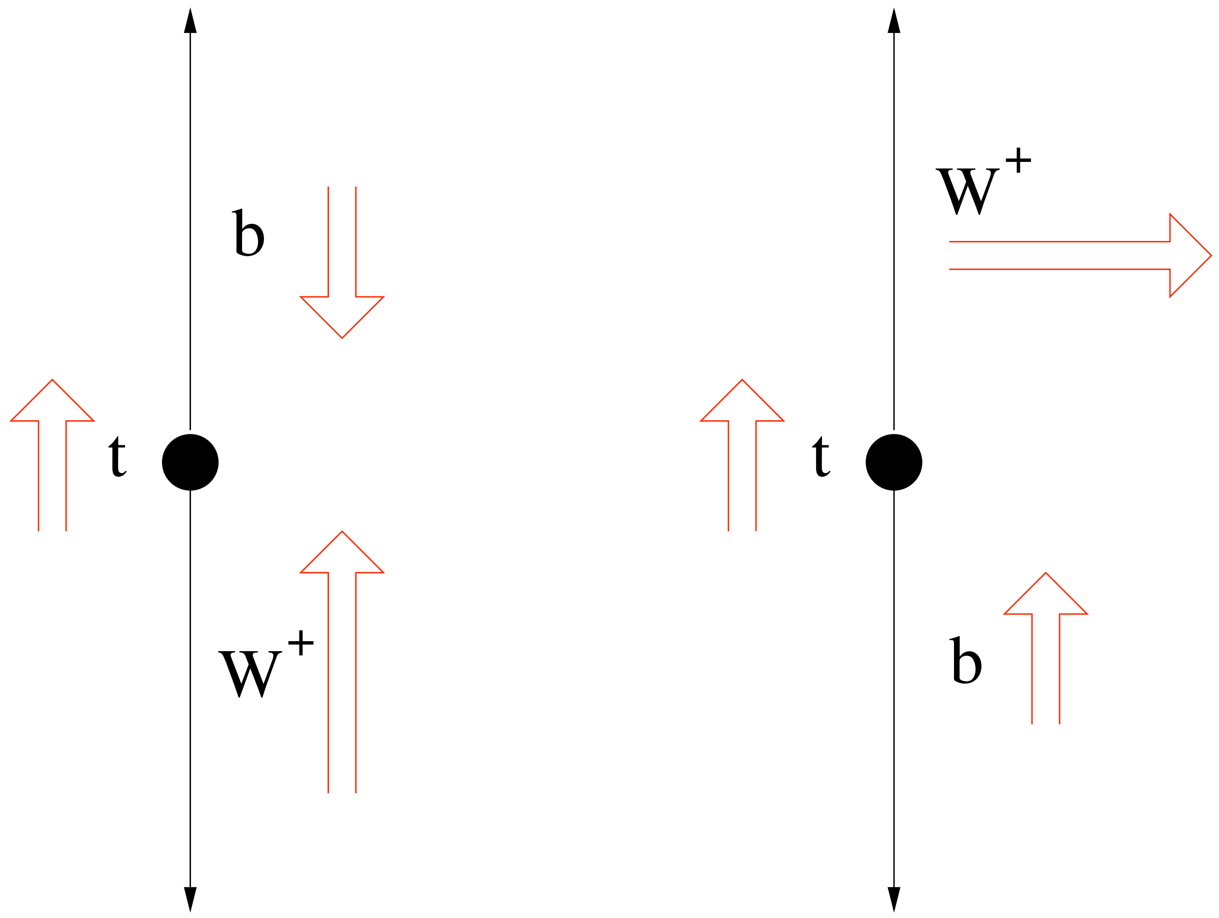
- Uncertainties for the highly boosted tops:
  - for highly boosted top jet: b-tagging efficiency is wired (~20%) L. March, E. Ros, B. Salvachúa ATL-Phys-PUB-2006-002
  - fake-b-tagging (~1%) for the QCD jet
  - top quark radiation effect
  - jet broadening (detector level)
  - PDF uncertainties
- Study of substructure of top and QCD jet can help distinguish top from QCD jet J.M. Butterworth, B.E. Cox, J.R. Forshaw

Top Polarization

- Daughter particles remember top polarization
- For ultra-relativistic top: helicity=chirality
  - Can do polarization analysis like it was done for the tau
  - A powerful method already mentioned in Gilad's talk
- We want to use P_T to probe top polarization: P_T is a directly measured quantity (c.f. For polarization method, need to use derived quantities with biases, like center of mass boost etc.)
  - Different from spin-spin correlation where you expand in s wave (for non-relativistic top)

Top Polarization

~30% ~70%

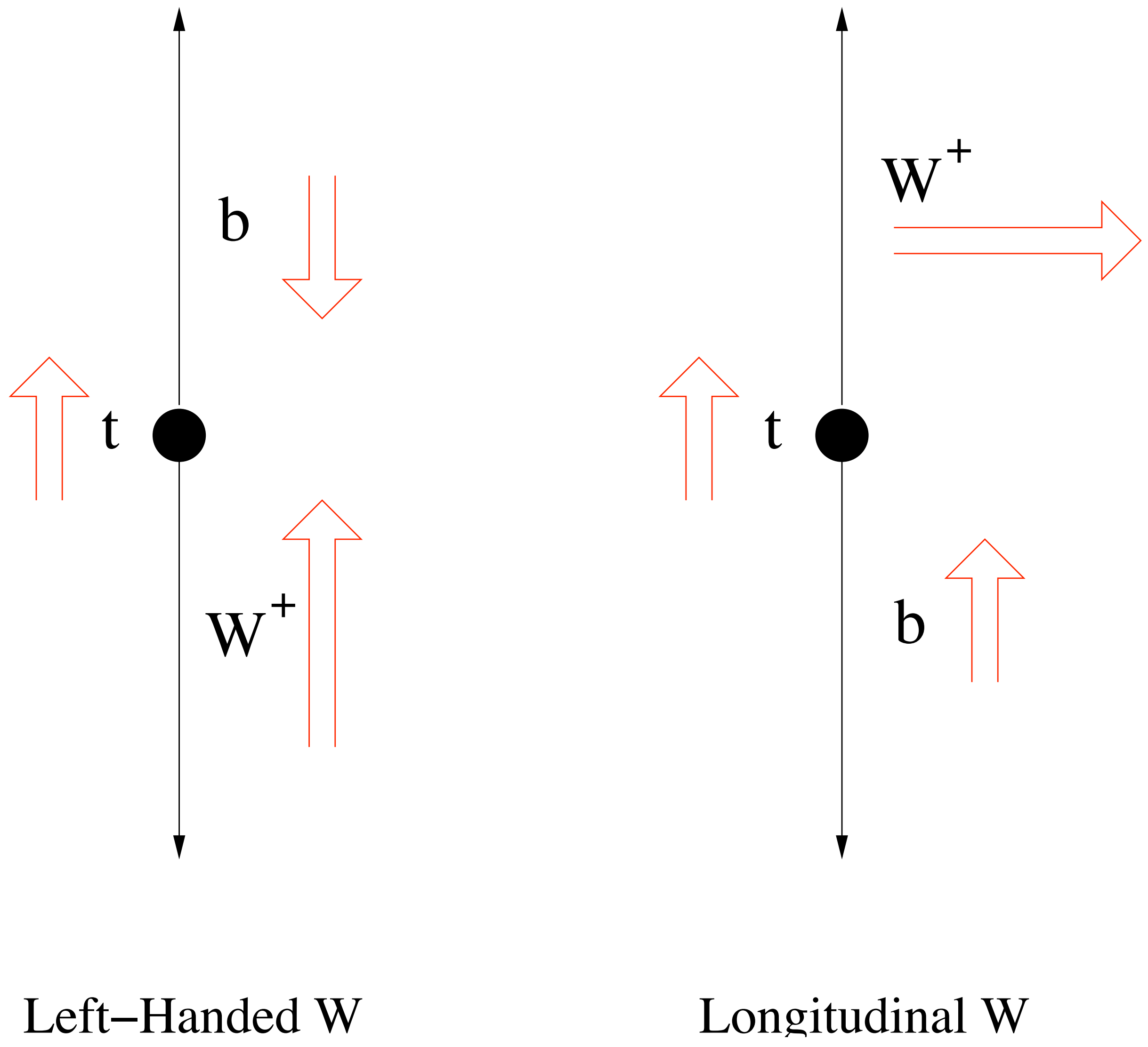


Left–Handed W Longitudinal W

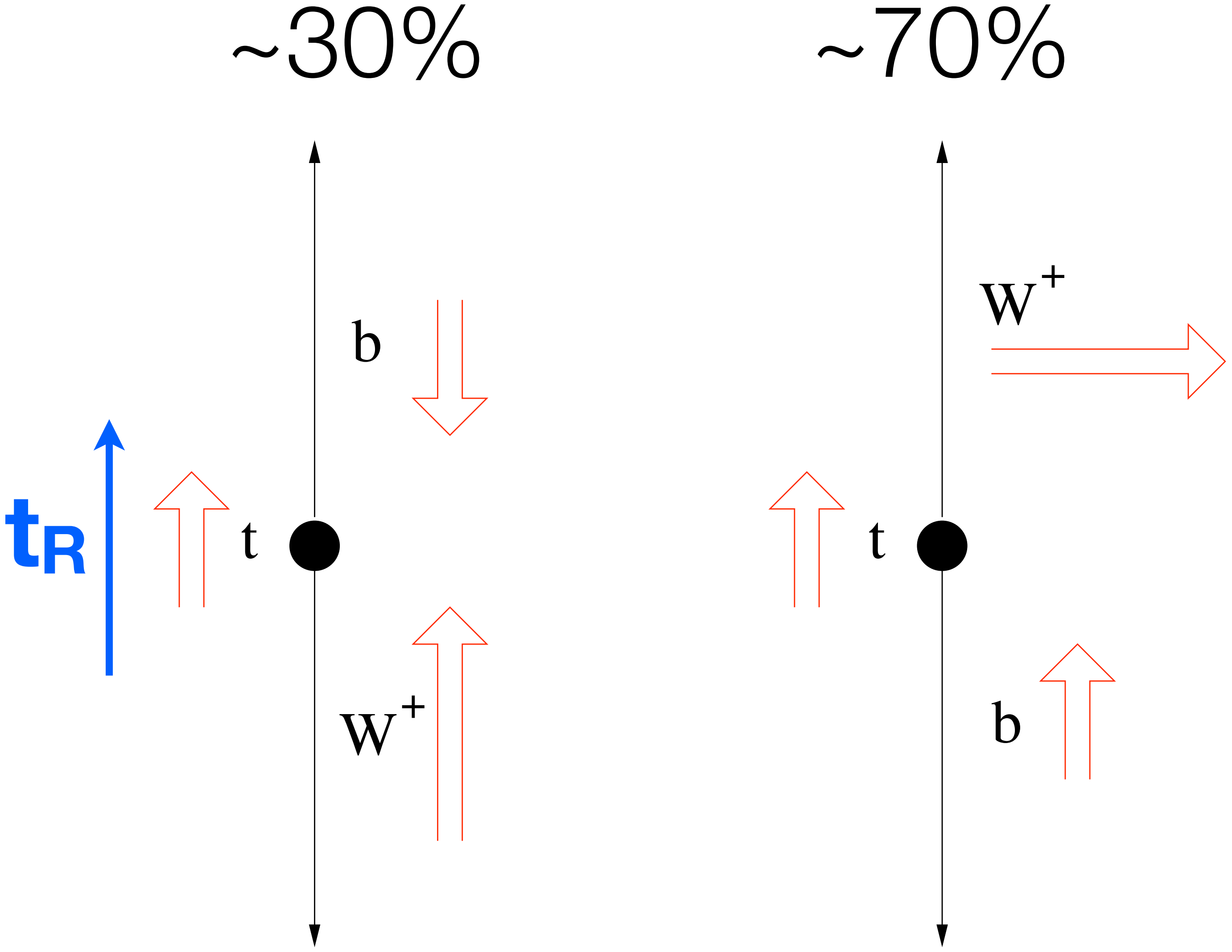
Top Polarization

~30% ~70%

t_R



Top Polarization



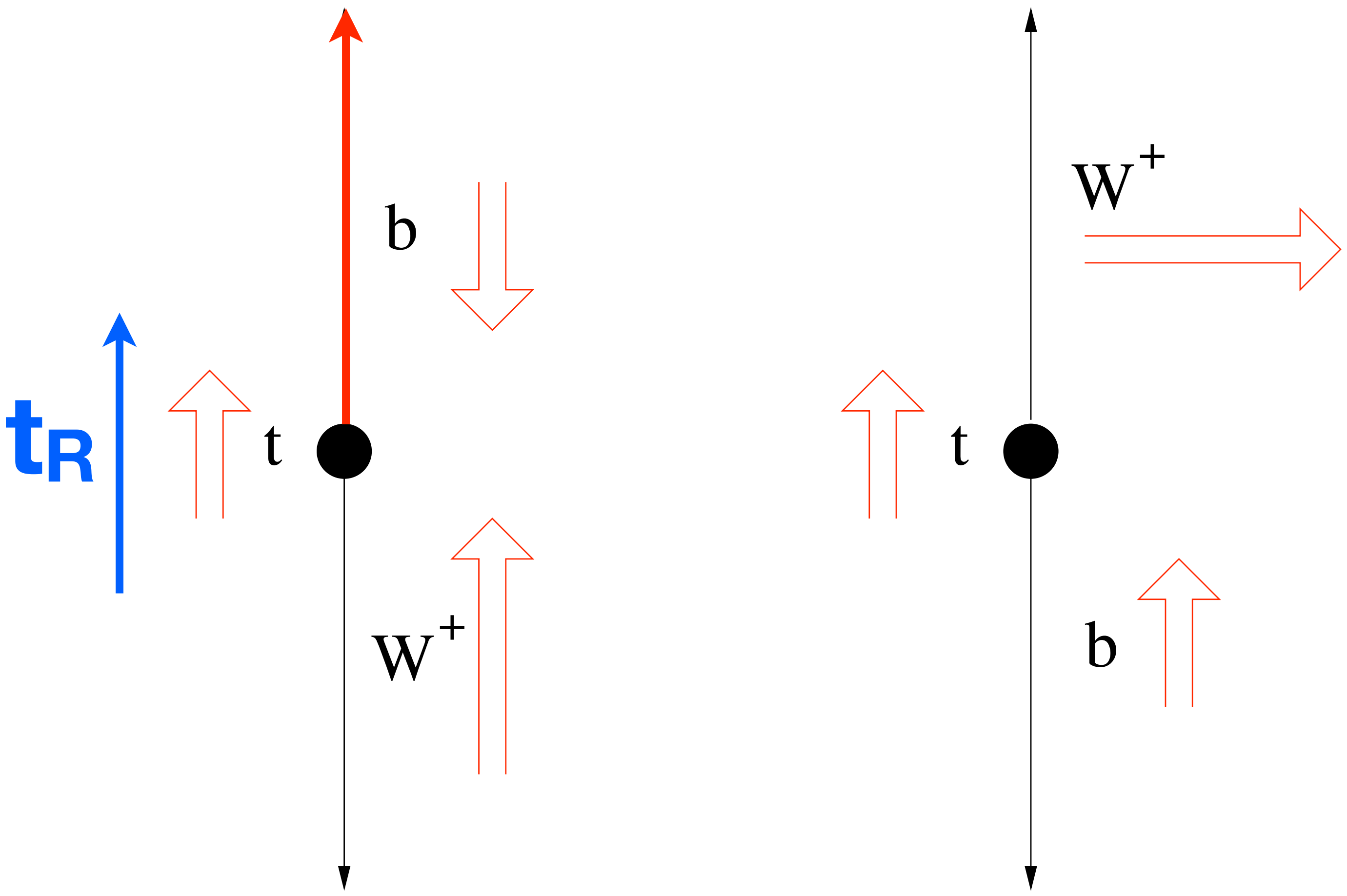
~30%

~70%

Left–Handed W

Longitudinal W

Top Polarization



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Longitudinal W

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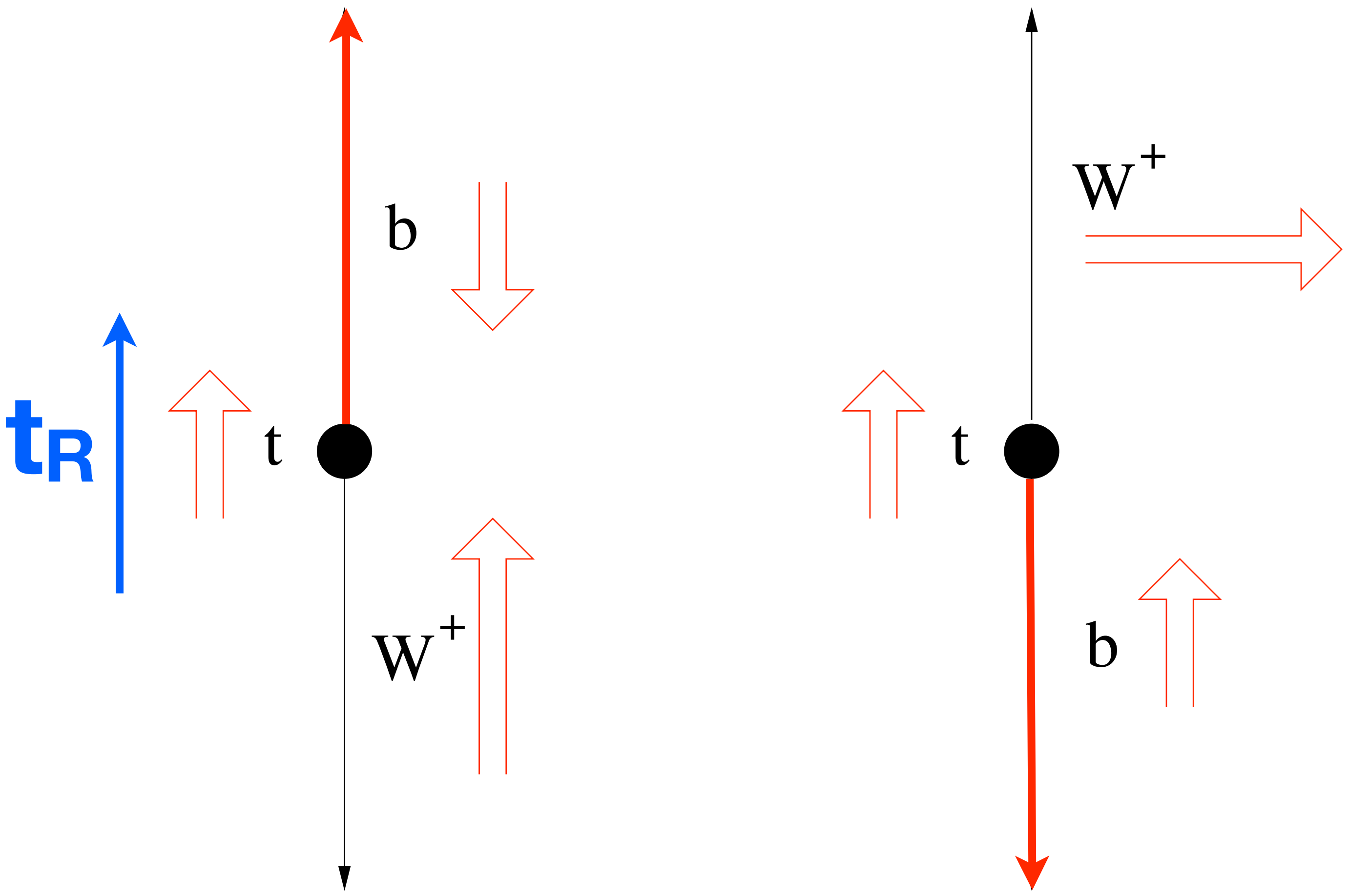
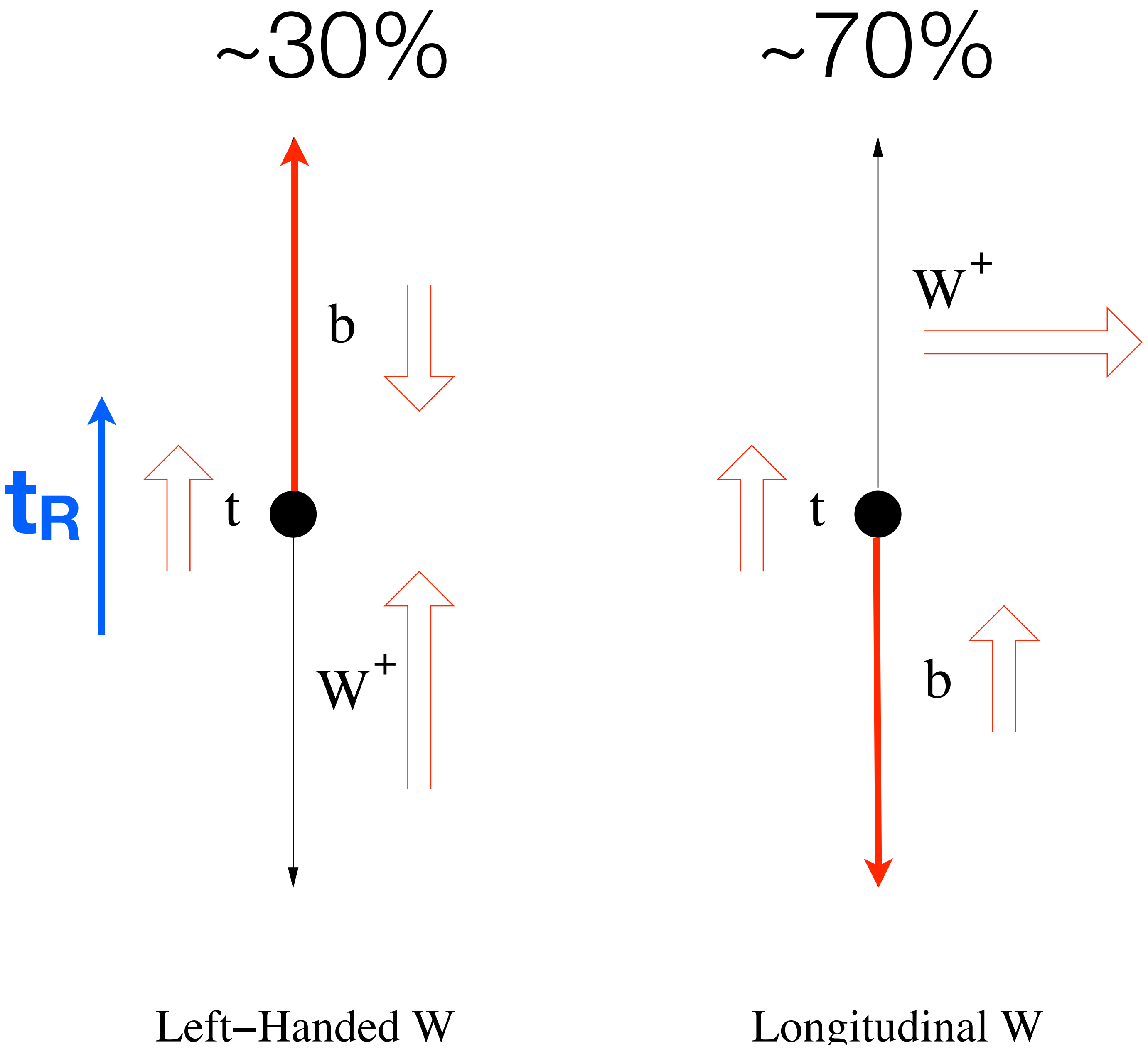


Left–Handed W Longitudinal W

Top Polarization

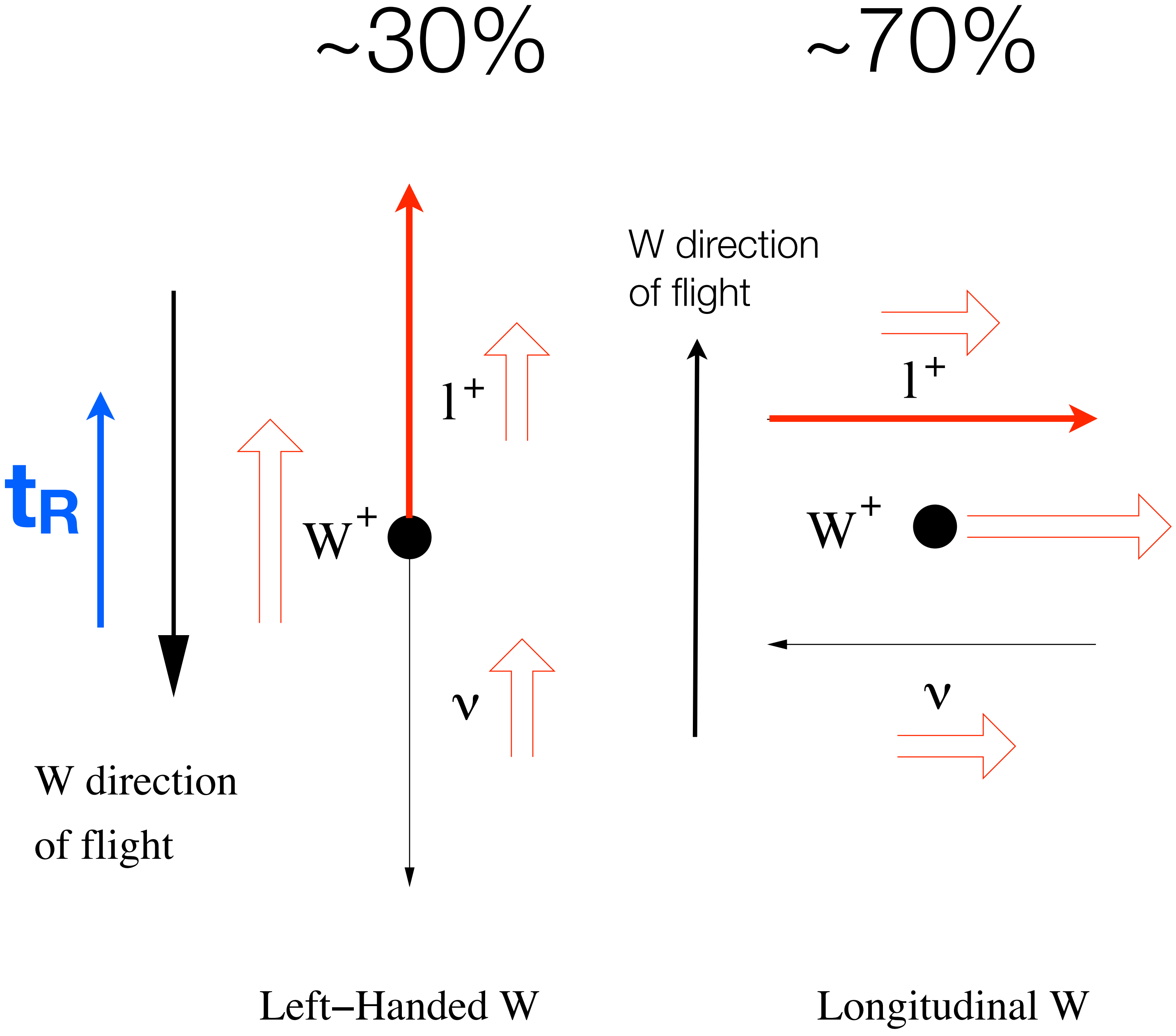
- b quark:
  - back-warded (soft P_T) for t_R
  - forwarded (hard P_T) for t_L
- For SM, parity even (PT distribution will be flat) ➔ look for new Physics where parity is violated



Top Polarization

- lepton:forwarded for t_R

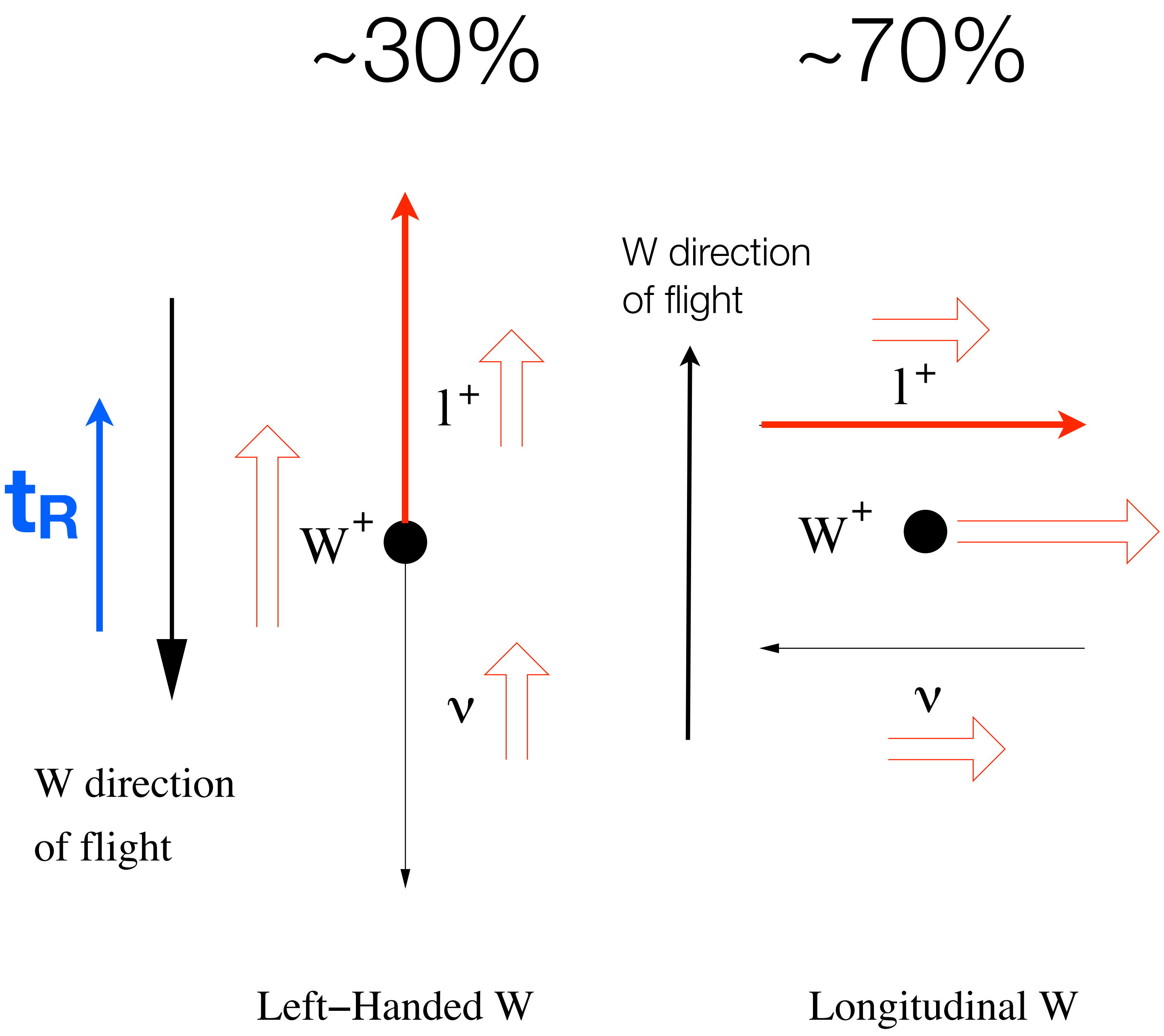
  back-warded for t_L



Top Polarization

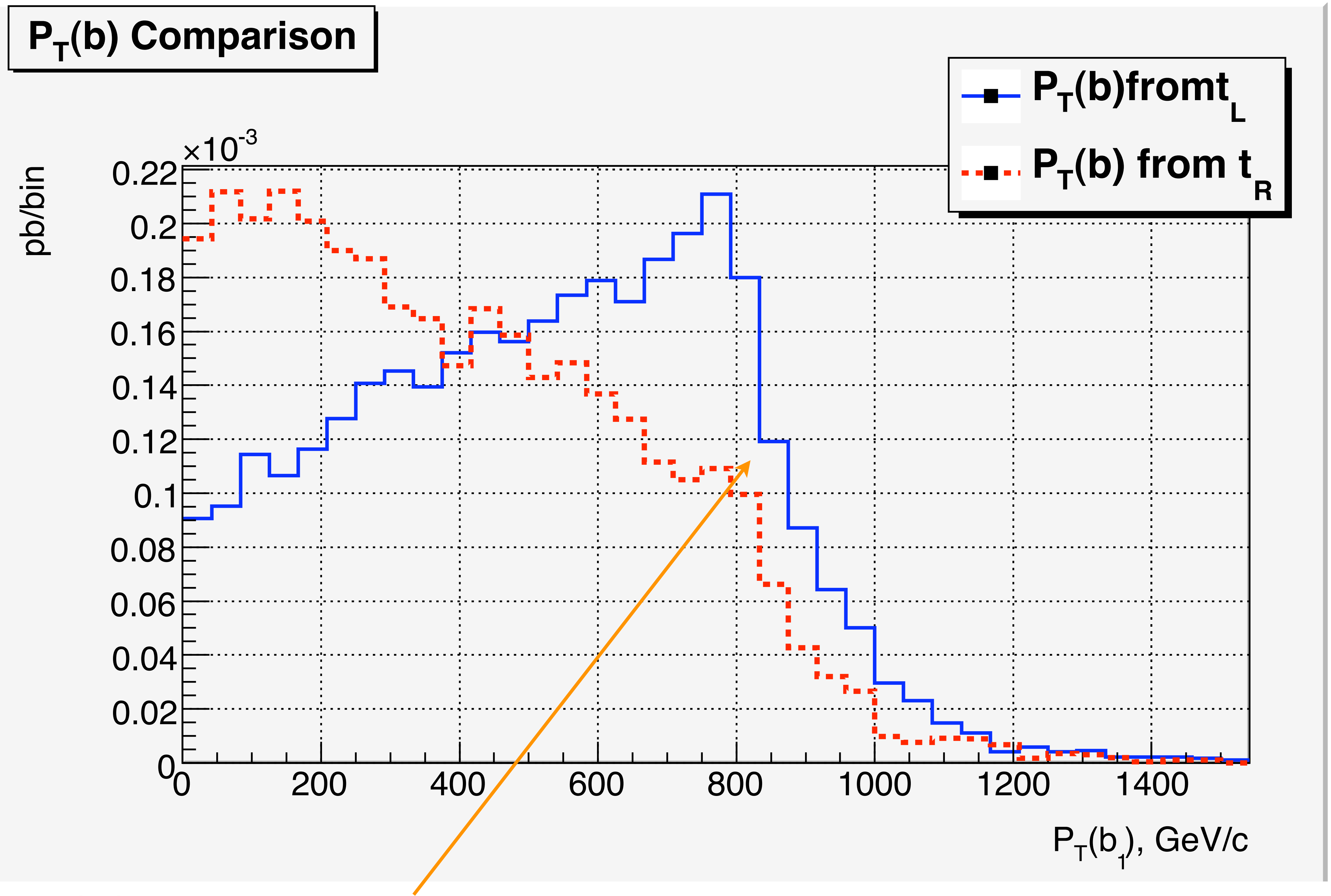
- lepton:forwarded for t_R

  back-warded for t_L



For Boosted Longitudinal W: letpon is forwarded

p_T(top) > 1TeV

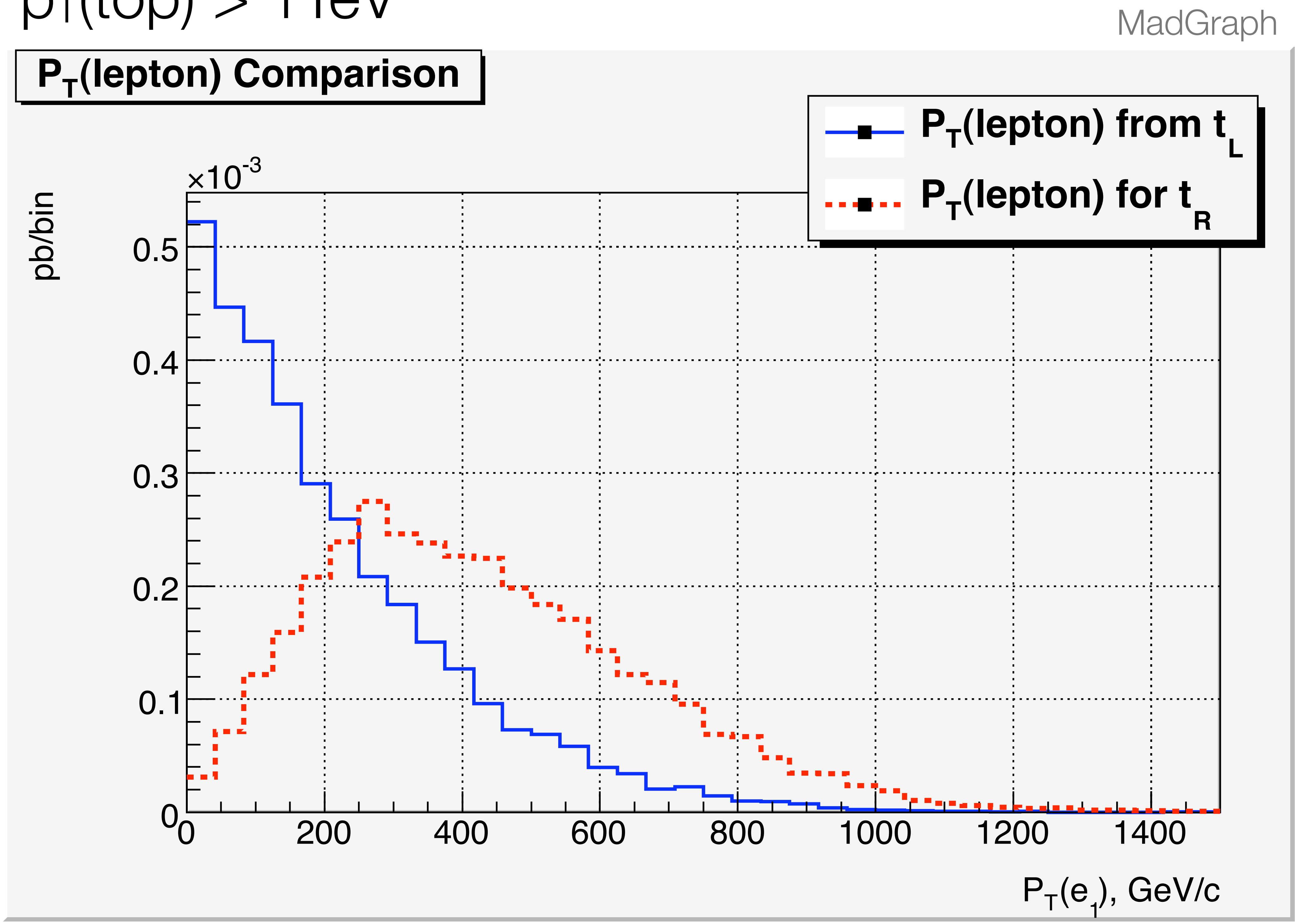


P_T(b) is limited by W boson mass

Hadronic Top

b quark as a spin analyzer

$p_T(top) > 1TeV$



- for example with the KK gluon, you'll see suddenly only leptons/bs that follows the RH curves

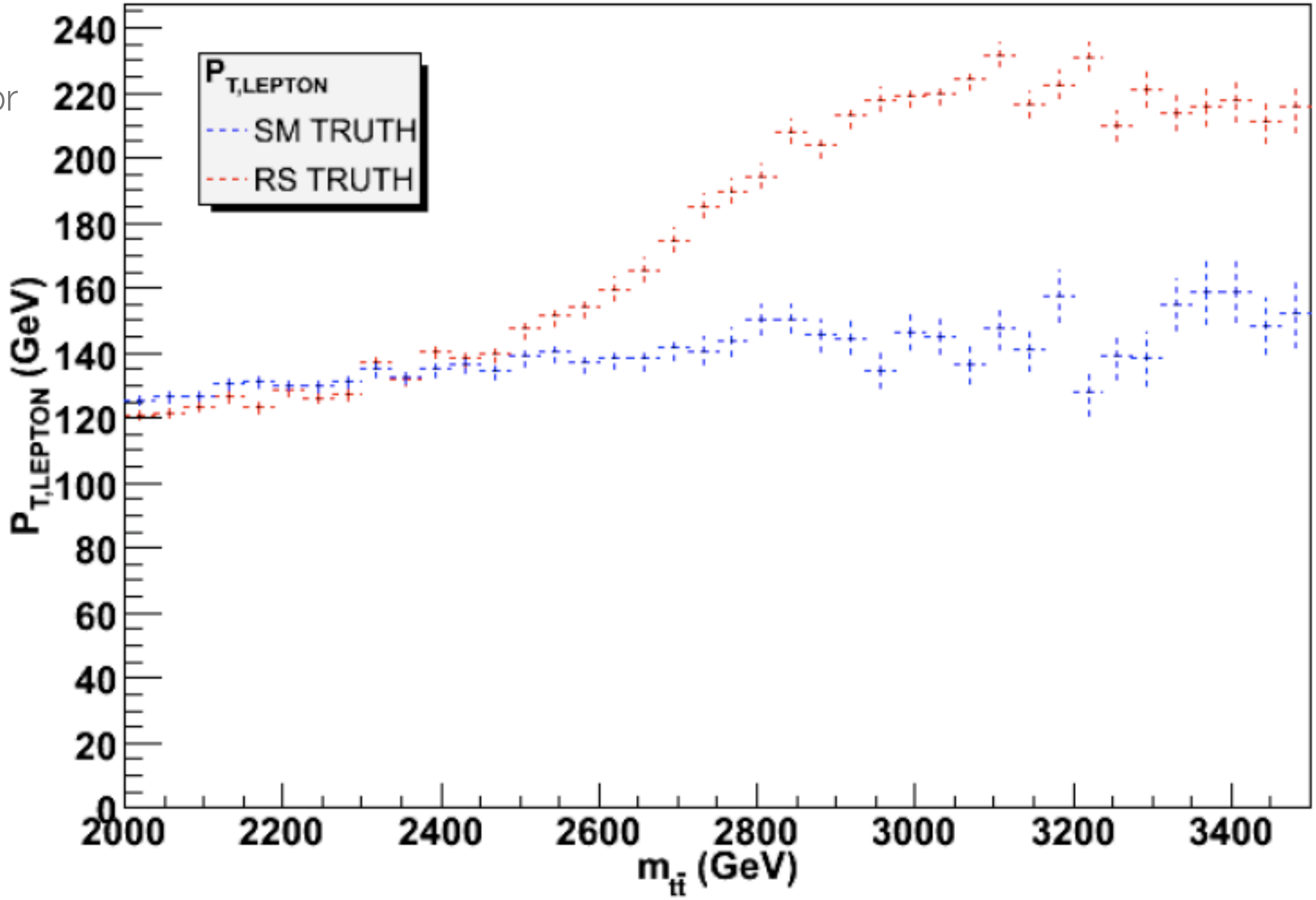
Leptonic Top

charged lepton as a spin analyzer

$P_{T,LEPTON}$

S. L., G. Perez, J. Virzi
A. T. Holloway

Sherpa (CKKW)
Without Detector
Simulation

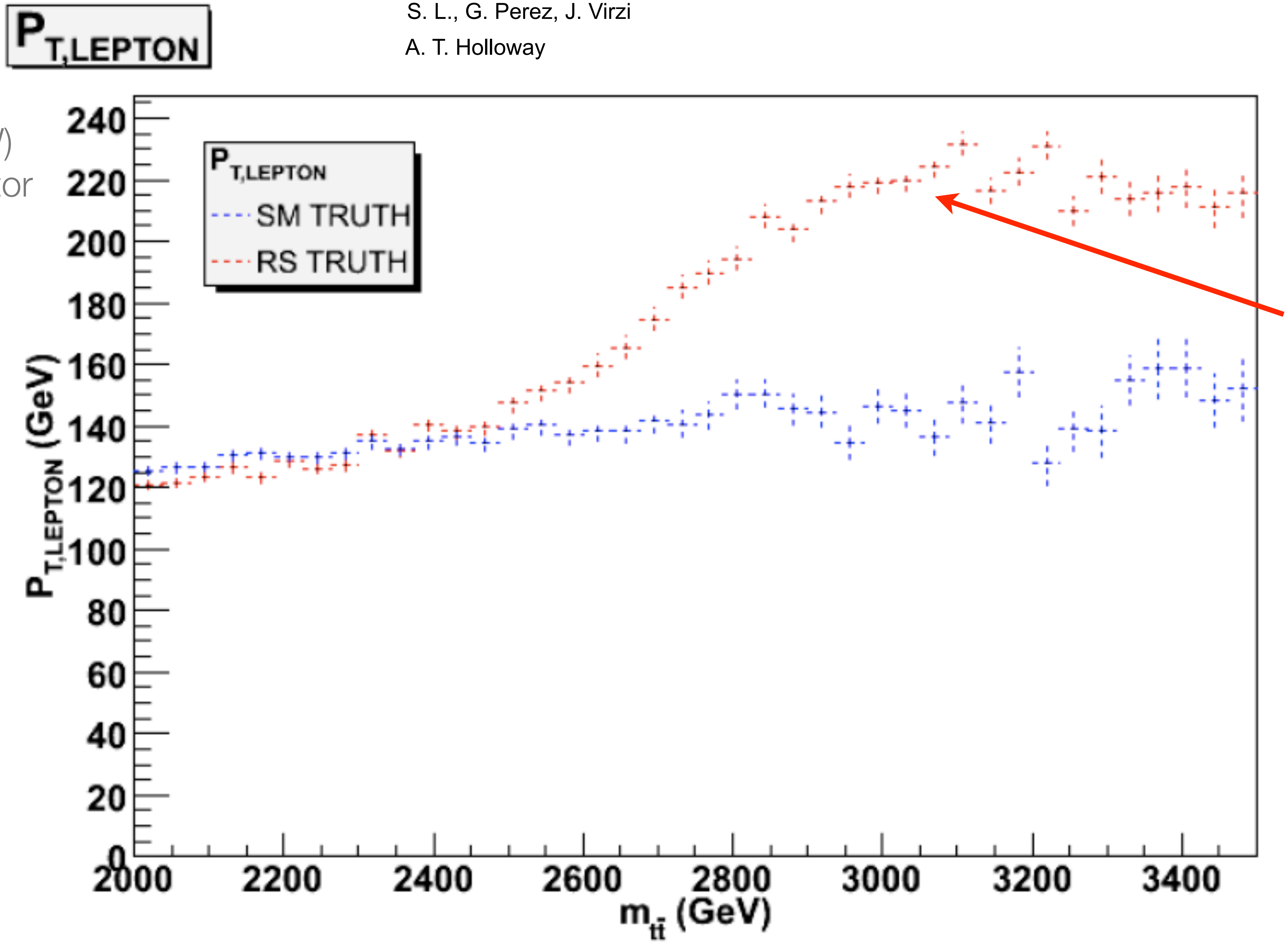


Example: KK gluon

lepton PT is harder near the KK gluon plateau

S. L., G. Perez, J. Virzi
A. T. Holloway

Sherpa (CKKW)
Without Detector
Simulation

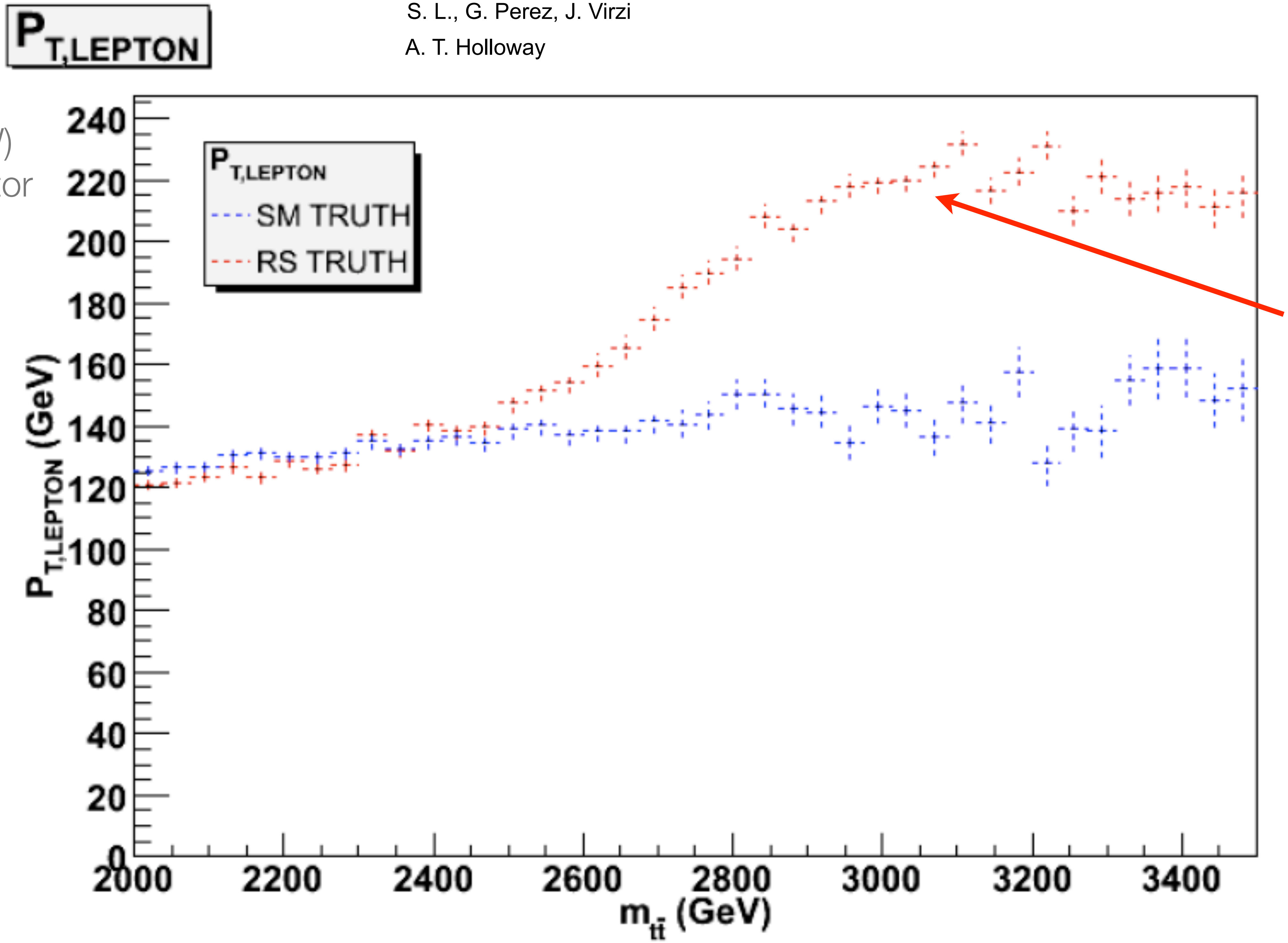


Example: KK gluon

lepton PT is harder near the KK gluon plateau

S. L., G. Perez, J. Virzi
A. T. Holloway

Sherpa (CKKW)
Without Detector
Simulation



KK gluon bump

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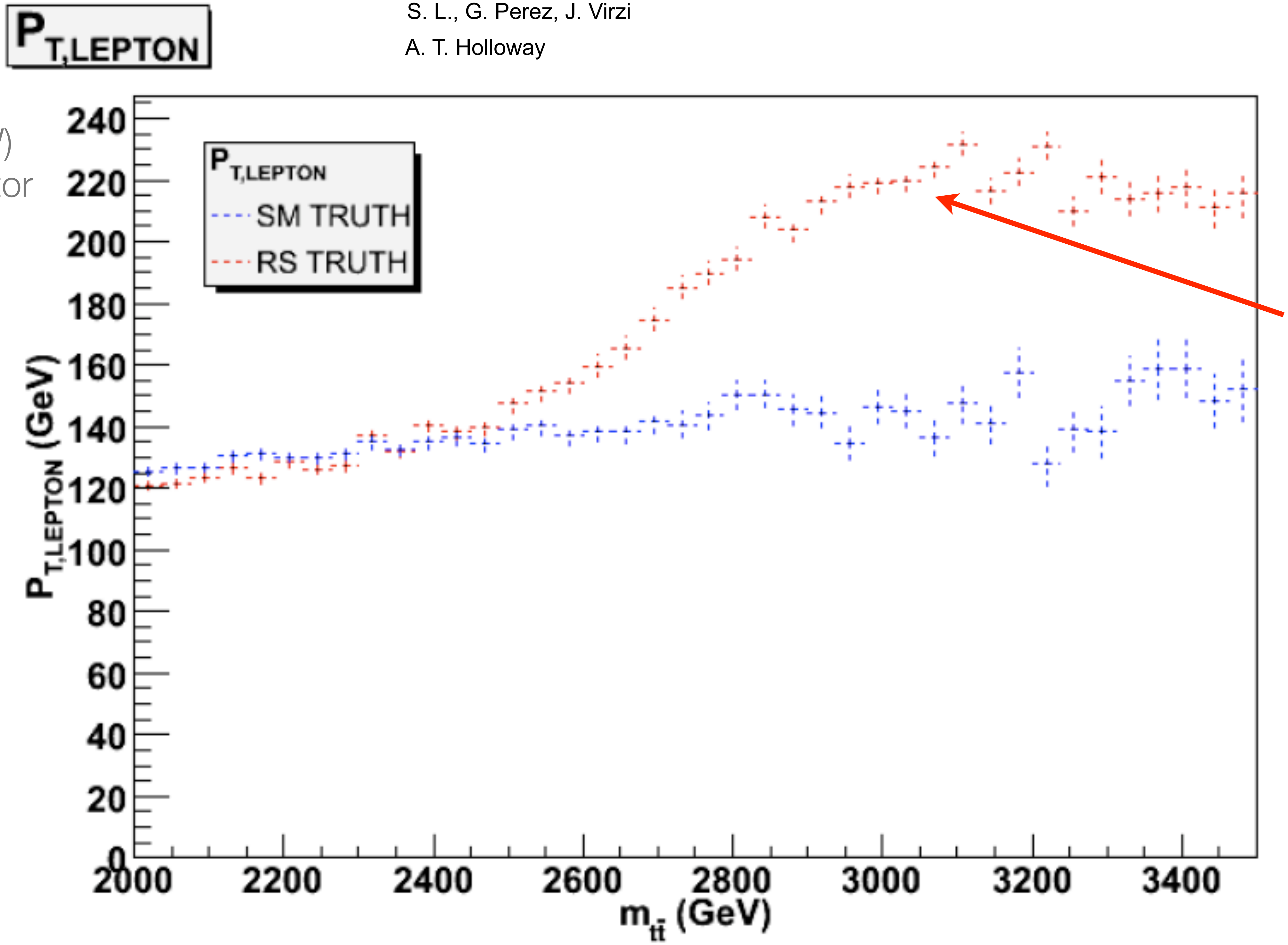

KK
gluon
bump

Also relevant for SUSY: heavy stop decaying into top and wino

Example: KK gluon

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Top Polarization

p_T(top) > 1TeV

MadGraph

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- Average ΔR: 0.46 (t_L)/ 0.29(t_R)

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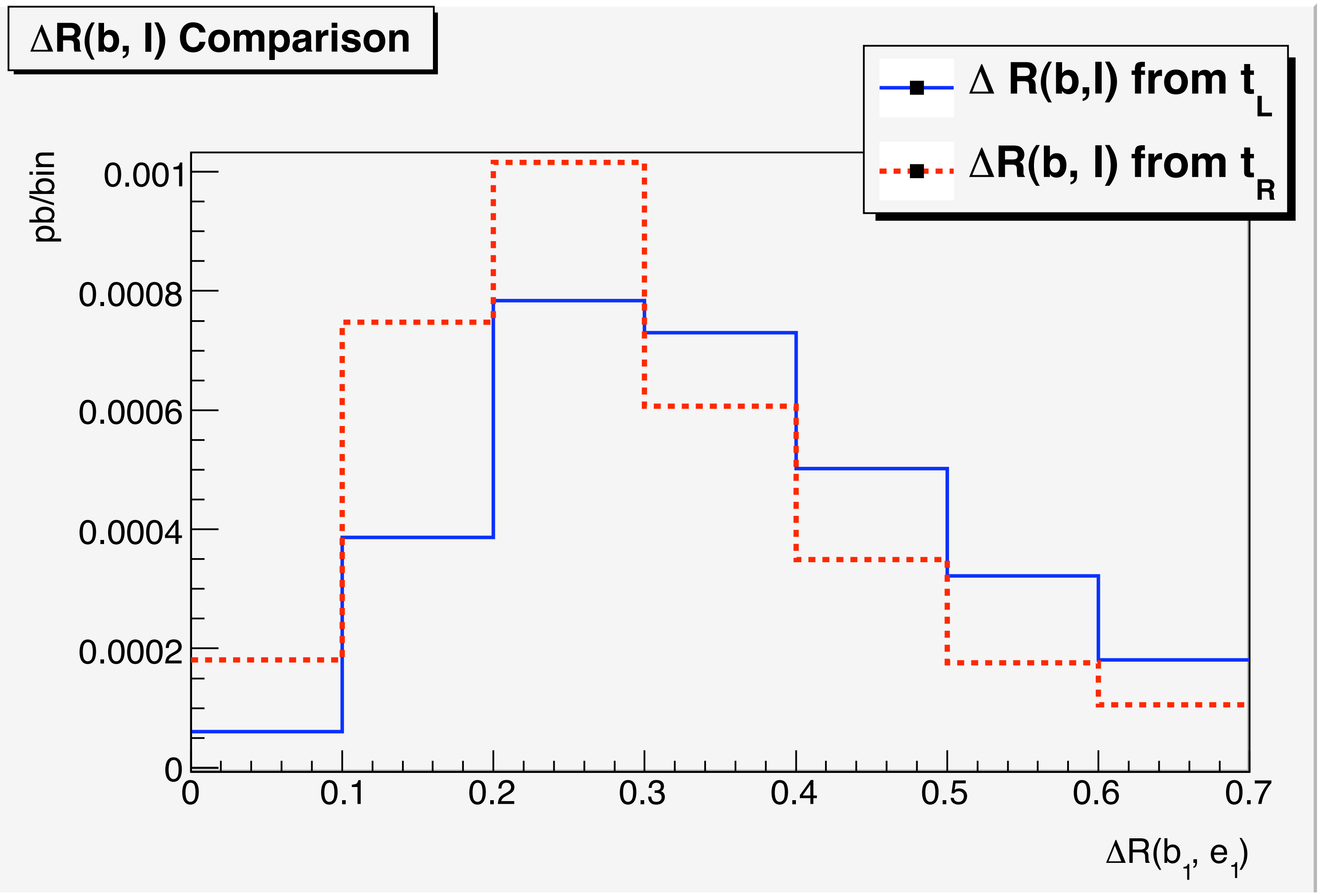

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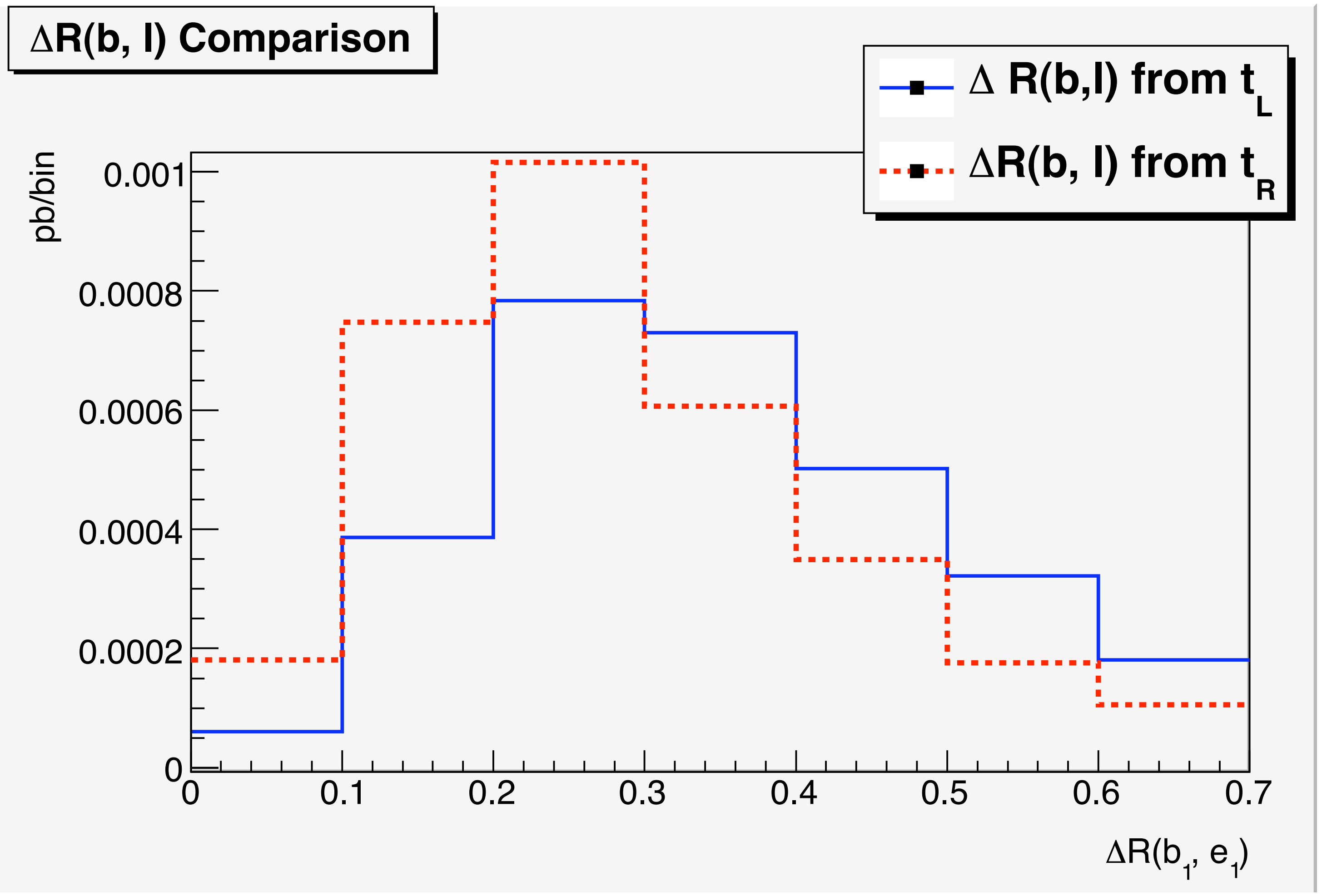

- For choosing a cone size, can be biased for **t_R** (if cone size is small), as the average ΔR is smaller than that of **t_L**

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- ΔR difference (b quark from top decay)
- Average ΔR: 0.27 (t_L)/ 0.34 (t_R)

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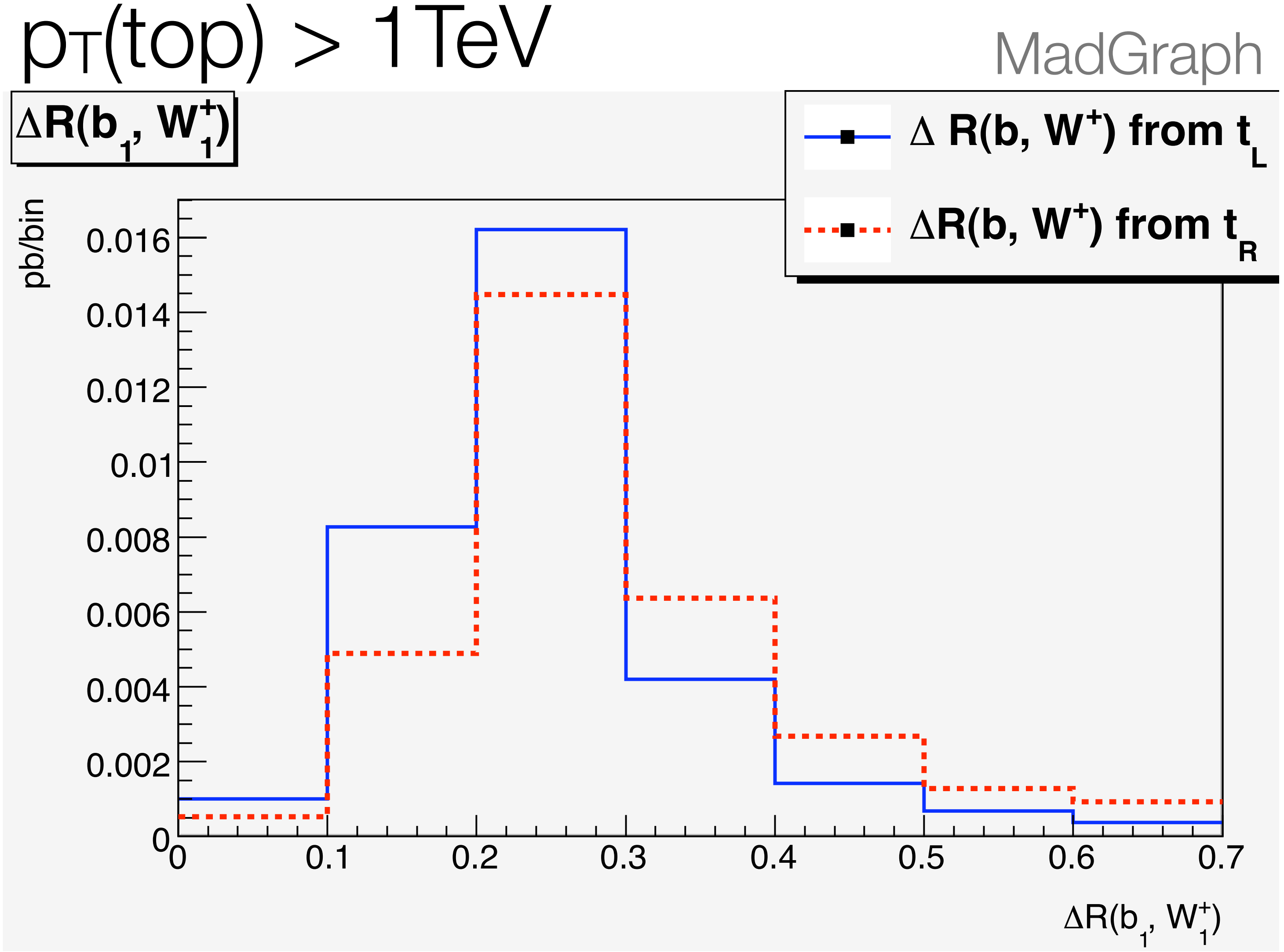

- For choosing a cone size, can be biased against **t_R** (if cone size is small), as the average ΔR is larger than that of **t_L**

Summary

- Challenges with highly boosted tops; decay products are highly collimated
- Identifying top with single jet mass might be a solution; need to distinguish top from the QCD Jet
- Have a simple (pseudo-rapidity independent) analytical handle from Factorization approach for QCD jet
- P_T of b quark (lepton) can be used to analyze hadronic (leptonic) top quark polarization
- Our analysis is equally relevant for highly boosted W, Z (because of unitarity bound) and the boosted Higgs